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Final Report

July 1987

User's Guide and Program Description for a Tripped Roll Over Vehicle Simulation

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16. Abstract

Tripped rollover results when a vehicle slides sideways into a curb or other small obstruction which converts the vehicle's translational kinetic energy into rotation. Given the vehicle's center of gravity height and wheel track width, it can roll over given sufficient side velocity. This scenario is applicable to highway vehicles such as cars and trucks and off road vehicles as diverse as riding lawn mowers. Safety statistics show vehicle rollover to be a common accident mode, and this report describes a time domain simulation program developed to analyze the influence of various vehicle and scenario parameters.

The program is based on a general purpose microcomputer program which was designed to simulate dynamic systems defined in relatively simple specification syntax, and provide the user with insightful graphical displays. The program currently runs on an IBM-PC© or compatible. The report describes the vehicle model equations of motion, provides program user's instructions, and gives examples of program operation.

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INTRODUCTION

A. PROBLEM, OBJECTIVES, AND PURPOSE

As part of a current crash avoidance research initiative, NHTSA has been looking into the relative occurance of various types of accidents. When car size is taken into account, it has been found that the likelihood of roll over increases with decreasing car size. In an effort to uncover factors that might contribute to this accident in- lvement mode, NHTSA has been working with a relatively simple model for describing tripped roll overs (Ref. 1). This model accounts for a vehicle sliding sideways into a curb and can predict roll over potential based on initial side velocity, and certain details associated with the location of the vehicle center of gravity and roll characteristics of the vehicle's sprung mass. This modeling approach appears to have some potential for expanding our knowledge of the factors contributing to vehicle roll over involvement in accidents, but the generality of the model must be expanded in order to fully explore this method.

The Ref. 1 vehicle/curb encounter model is fairly restricted to vehicle velocities normal to the curb, with both wheels encountering the curb simultaneously. The objective of the work reported herein was to develop an expanded computer model to include several arbitrary initial conditions: 1) curb encounter angle; 2) vehicle lateral velocity; 3) vehicle yawing rate. The time/force relationship for the wheel/curb impact was also to be modelled. The Ref. 1 model assumes complete conservation of the impulse momentum associated with wheel/curb side impact. Some consideration was also to be given to energy dissipation and storage due to wheel/suspension deformation and elastic deflection. Elaborate geometric/structural models were not desired here, but the model should account for simple effects such as deformation and compliance, and damping associated with the combined elastic deformation of the tires, wheels, and suspension.

The purpose of the work requested under this task order is to provide a vehicle tripped roll over model that NHTSA can use to further explore factors associated with this accident mode. This working paper documents the implementation of the model in a computer program which allows initial conditions to be conveniently manipulated, and provides for convenient graphical output of results. This working paper documents the model equations (Appendix A), program structure and preliminary results (Section II), and includes user instructions (Section III).

B. BACKGROUND

A fairly simple momentum conservation model is developed in Ref. 1 to determine vehicle roll over given lateral impact with a curb. Given that both wheels simultaneously impact the curb, the critical lateral velocity for overturning is given by the equation

$$V^2 \geqslant \frac{2g}{M_T h_{cg}} I_o \left(\sqrt{1 + \left(\frac{T/2}{h_{cg}}\right)^2} - 1 \right) \qquad (1)$$

where

g = gravity

M_T = total vehicle mass;

I_o = total roll moment of inertia

h_{cg} = center of gravity height;

T = track width

It is clear from Eq. 1 that the critical velocity for tip over directly decreases with the ratio of center of gravity height to one-half of the track width. Therefore:

$$\text{Roll Over Tendency} = \frac{h_{cg}}{T/2} \qquad (2)$$

with the roll over tendency increasing with decreasing critical velocity. A survey was made of a range of domestic and foreign cars, and the distribution of the roll over tendency parameter is plotted in Fig. 1. The average runs about 0.75 for domestic cars, while the average is higher (about 0.79) for foreign cars indicating a potentially higher roll over tendency for foreign cars.

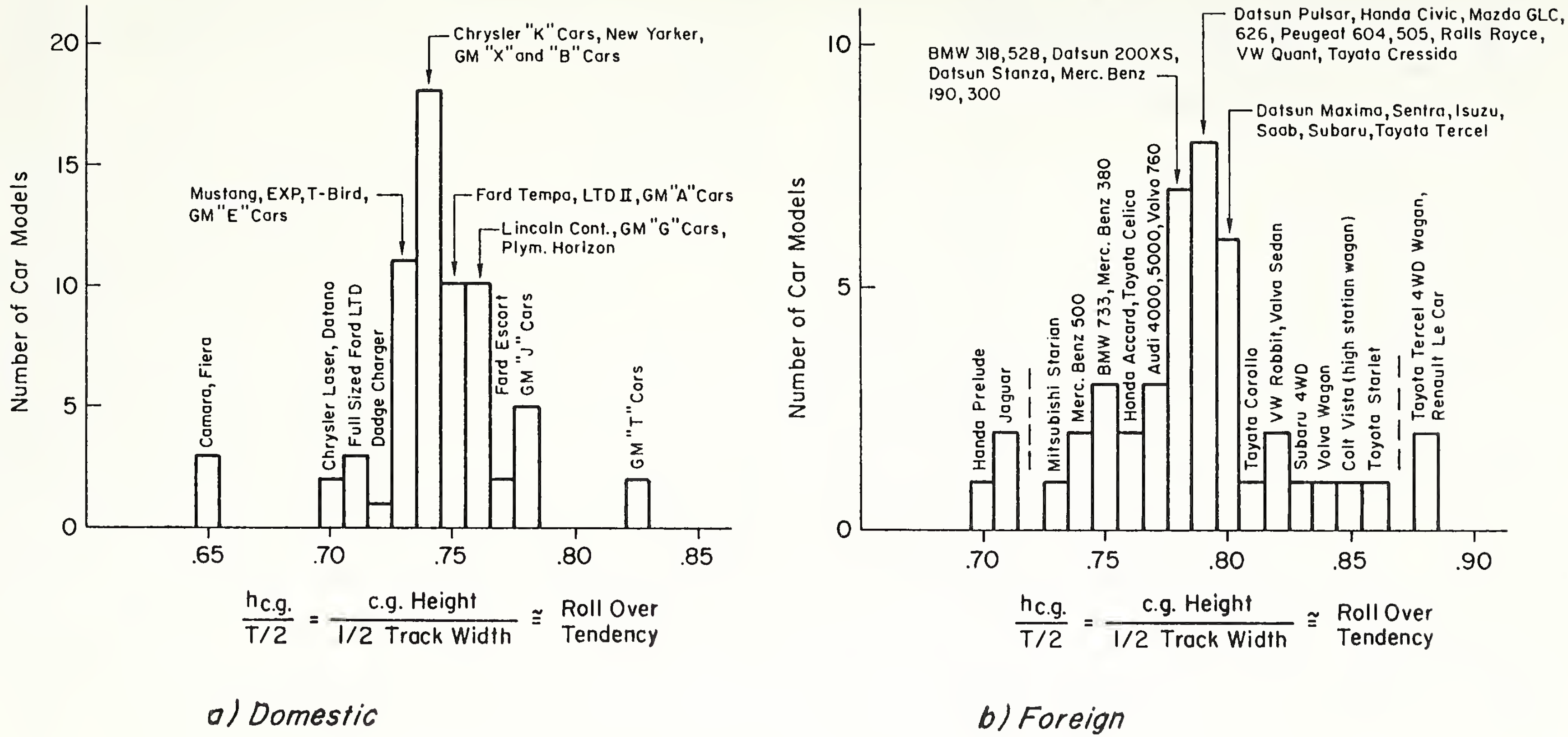


Figure 1. Roll Over Tendency Distributions for Domestic and Foreign Cars

The conditions leading up to roll over accidents are not very well documented in accident data bases. We do have some experimental data from a braking experiment, however (Ref. 2), where the vehicle could be configured to cause the rear brakes to lockup first under significant deceleration conditions (the stopping task required about 0.3 g deceleration). Rear brake lockup can lead to directional instability (Ref. 2) and yaw rate was recorded for all test runs. The distribution of yaw rate was analyzed as illustrated in Fig. 2. Data analysis also considered the covariation of heading angle and speed as the vehicle encroached on the cone delineated lane layed out for the braking task. These results are shown in Fig. 3. The data in Figs. 2 and 3 thus gives some indications of conditions which might lead to tripped roll over.

In the next section, we will describe the design and validation of the computer program which was prepared to analyze the the roll over tendencies of conditions such as illustrated in Figs. 2 and 3.

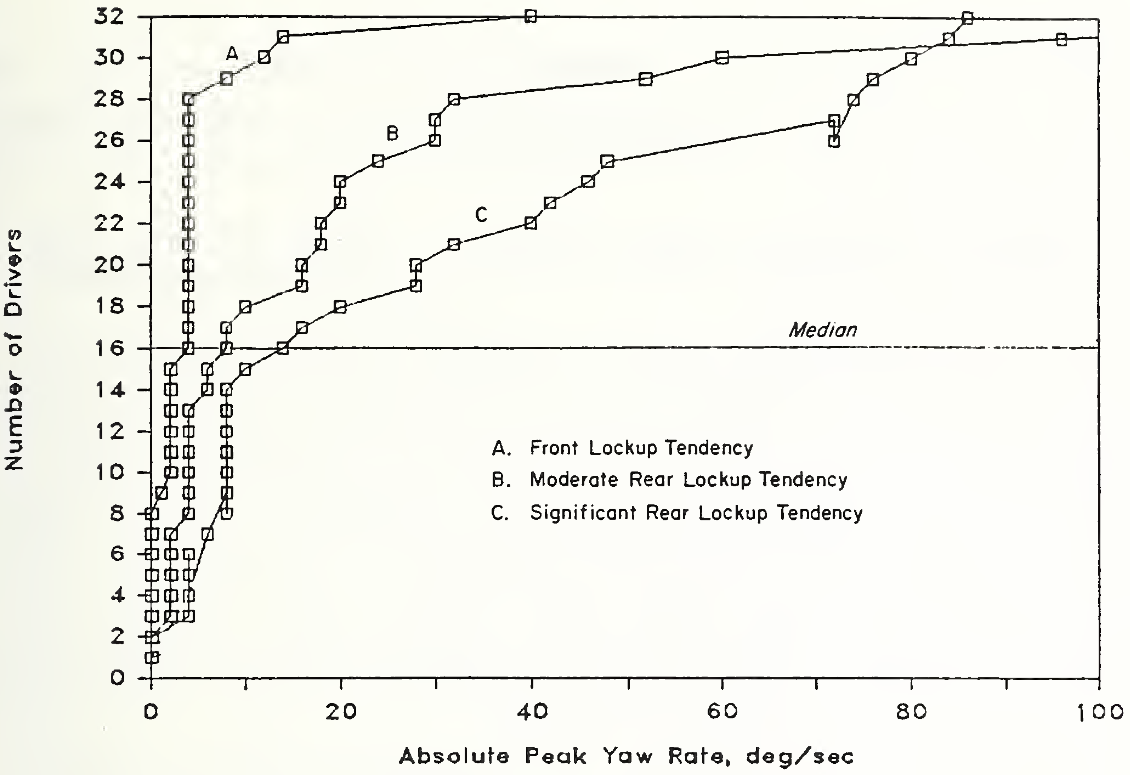


Figure 2. Distribution of Absolute Peak Yaw Rate During Braking Tests

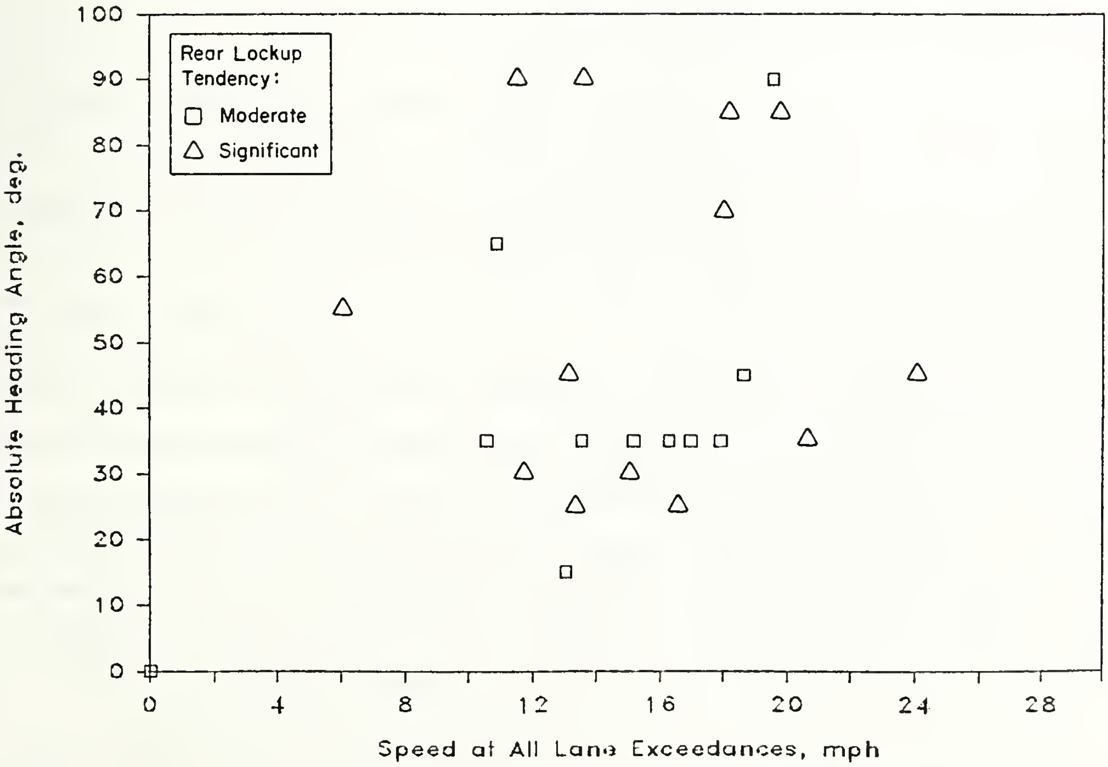


Figure 3. Heading Angle vs. Speed at Lane Exceedance Under Rear Wheel Lockup Conditions

SECTION II

PROGRAM DESCRIPTION

A. DEGREES-OF-FREEDOM AND DYNAMIC MODES

The computer programs developed during this project simulate a car sliding into a curb using a multi degree-of-freedom model and various dynamic modes. The degrees-of-freedom include vertical and horizontal translation (no forward translation), roll, pitch, and yaw. A simplified version of the model referred to as TRIP has no separate sprung mass. A more complex version of the model, referred to as SPTRIP includes separate sprung mass roll, lateral translation and heave degrees-of-freedom. Additional model components simulate tire sliding and normal forces, suspension springs, a lateral sprung mass bushing force, and a mode that simulates the reaction force from the curb due to vehicle impact. For a detailed explanation and listing of the equations and modes the reader is referred to Appendix A.

B. INPUT AND OUTPUT FEATURES

The program is designed for user ease. The vehicle characteristics (track width, sprung and unsprung masses, tire damping, etc.) are located in a file, which is then read into the program (refer to Appendix B). The user must only enter the data file name and the vehicles initial dynamic conditions. The program allows the user to choose between either iterating to the tip over velocity (within ±0.1 ft/sec) or running one set of dynamic conditions and seeing the outcome. The program also allows the user to input the dynamic variables that will be plotted. Any combination of variables for any set of conditions can be plotted. The user also must choose the time span that will be run and the iteration time increment. Finally the user is allowed to input one line of comments which will be included in the printed output. The preceeding input features will be further discussed in Section III-B.

The output consists of transient response plots of the four variables chosen during the input process. These plots are labeled complete with units and scales which will appear on the screen. The program automatically prints out (to a printer) the initial and impact conditions as well as the line of comments.

C. TEST CASES FOR SPTRIP (MODEL INCLUDING SPRUNG MASS)

This program is for the simulation of a dynamic vehicle model, therefore elementary test cases were run and evaluated to determine if the dynamic equations are behaving properly. Twenty-six different test cases were run to establish that all degrees-of-freedom were in working order. ıne ensuing test cases were run using vehicle parameters for a 1975 Chevy Nova. The values for these parameters can be found in the back of Appendix B. Definitions for the plotting variables are given in Section III.

1. Vertical Translation (Heave)

The first test case involves a car being dropped from above the ground (none of the tires are in contact with the ground). The purpose of this est was to show that both the tires and suspension springs damp out to constant values over a period of time. Figure 4 shows that over a short period of time both the center of gravity heights and velocities for each mass do indeed damp out. Note that the sprung mass has a natural frequency on the order of 2 Hz (i.e., ZSD).

2. Lateral Translation

Cases 2 and 3 (Fig. 5) show the car sliding both to the left and the right. The purpose for this was to show that the car slows to a stop due to sliding friction and comes to rest in either direction. These plots show that due to car sliding, small roll angles appear, as was expected due to the lateral deceleration induced by the lateral tire/road friction force.

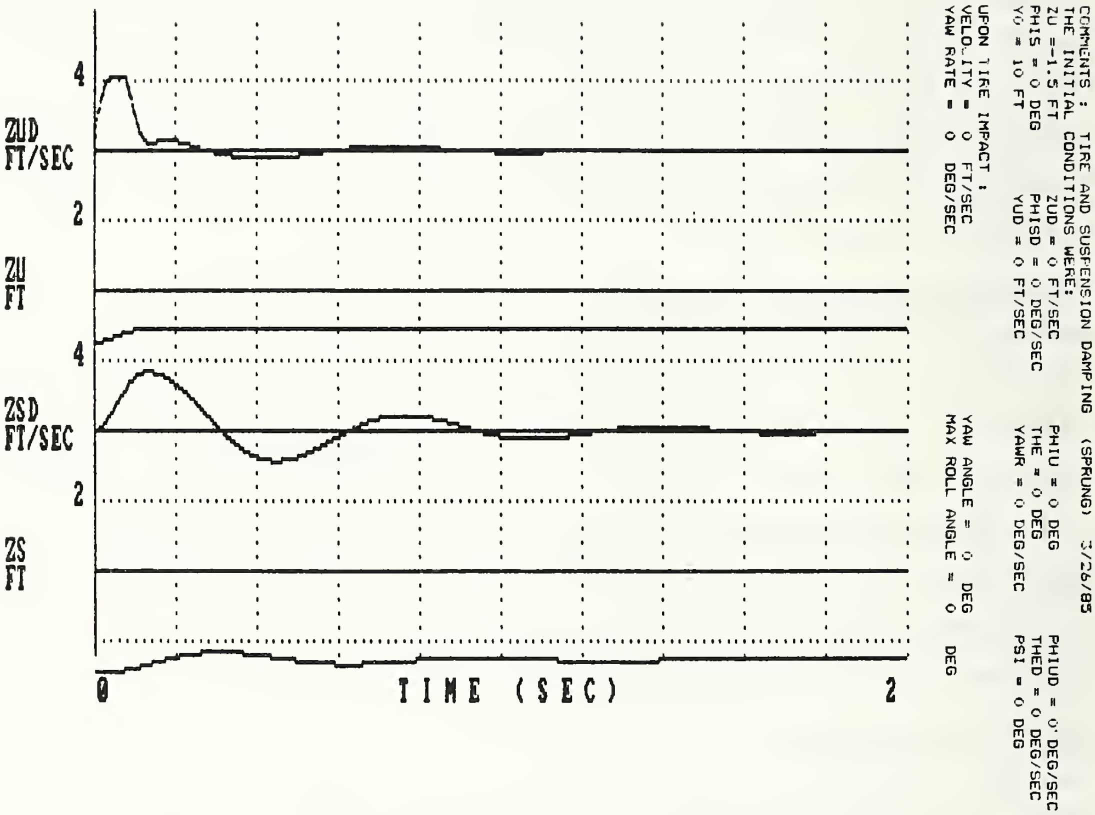


Figure 4. Test Case for Sprung and Unsprung Mass Vertical Degrees-of-Freedom

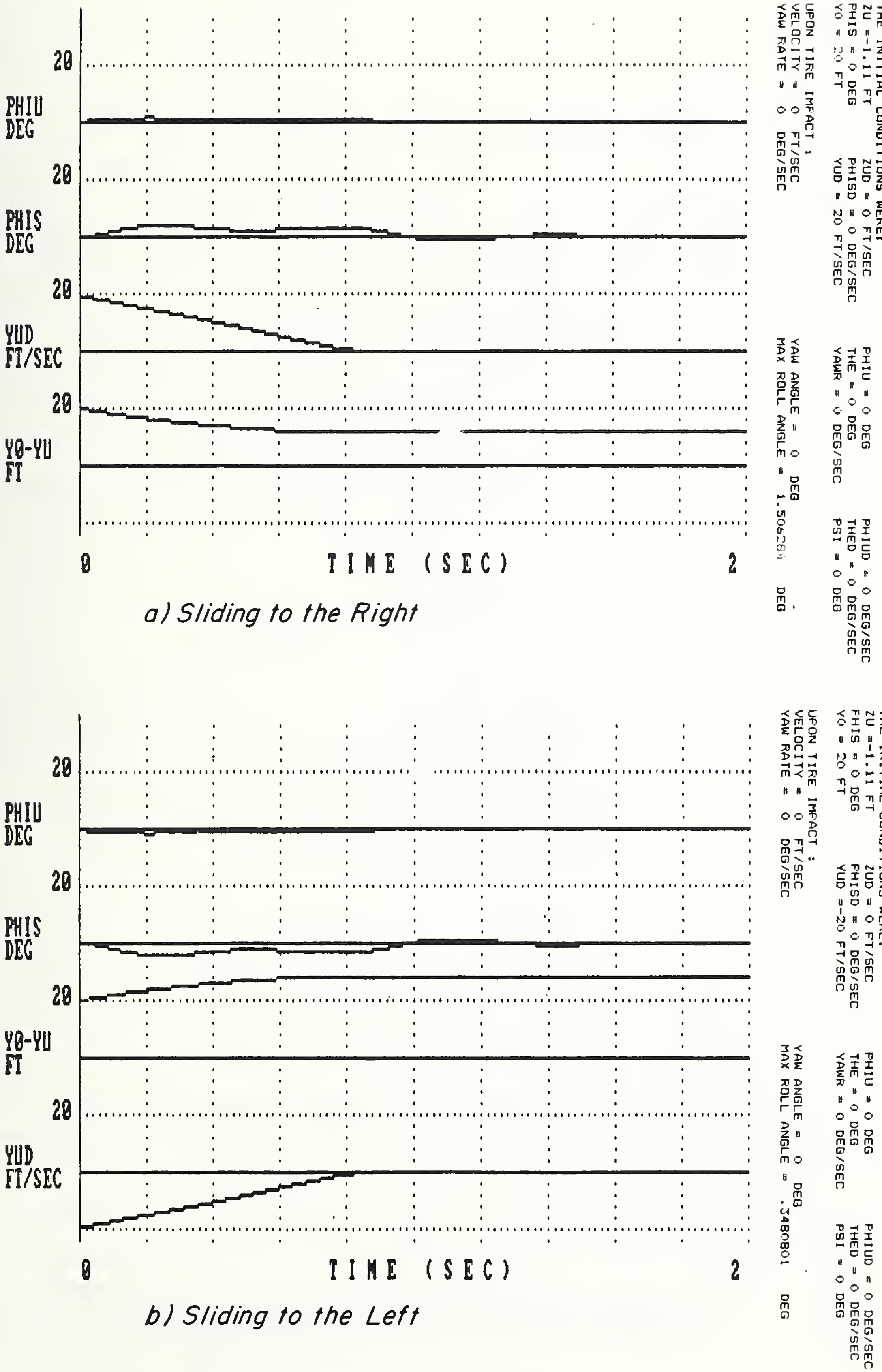


Figure 5. Test Cases for the Lateral Slide Degree-of-Freedom

3. Roll

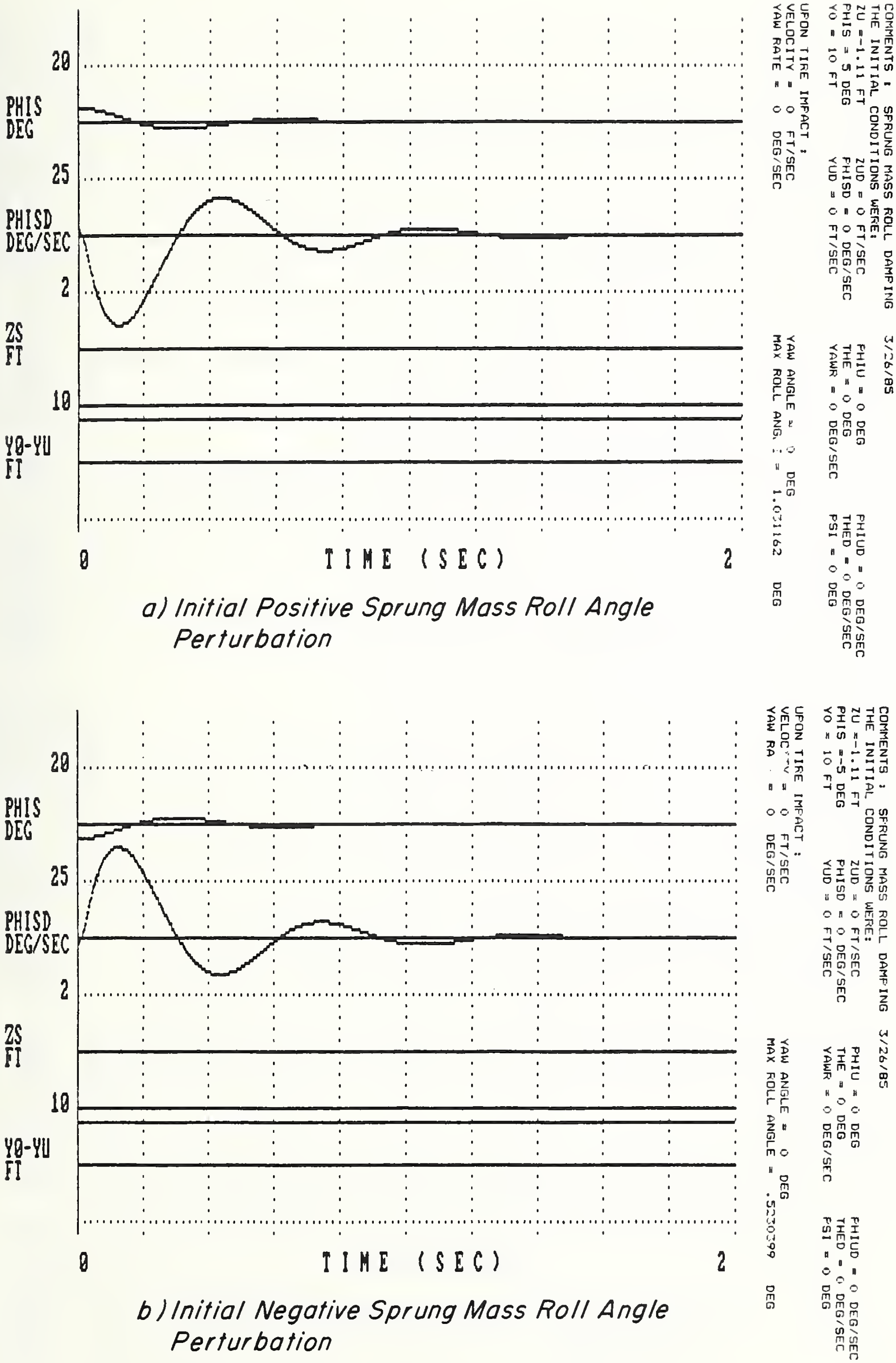
Cases 4-7 (Fig. 6) simulate the car's response in the roll degree-of-freedom. In all the cases tested a given roll angle produced a convergent roll reaction in both the sprung and unsprung masses. In the case of the sprung mass, it was tilted to a 5 deg angle and released while the unsprung mass angle remained zero. Figures 6a and 6b show that the resulting motion of the system converged to zero for both positive and negative initial angles, with a natural frequency on the order of 2 Hz. For the case involving the unsprung mass the car was tilted to an angle, with either the right or left wheels remaining in contact with the ground, and released. Figures 6c and 6d show that like the sprung mass, the system damps out for both positive and negative initial angles.

4. Pitch

Cases 8 and 9 (Fig. 7) represent the pitching degree-of-freedom. For these cases either the front or the rear tires are lifted off the ground (while the others remain in contact) and are released. The resulting motion is convergent and is shown in Fig. 7a for positive initial pitch angle, and in Fig. 7b for a negative angle.

5. Yaw (Heading Angle)

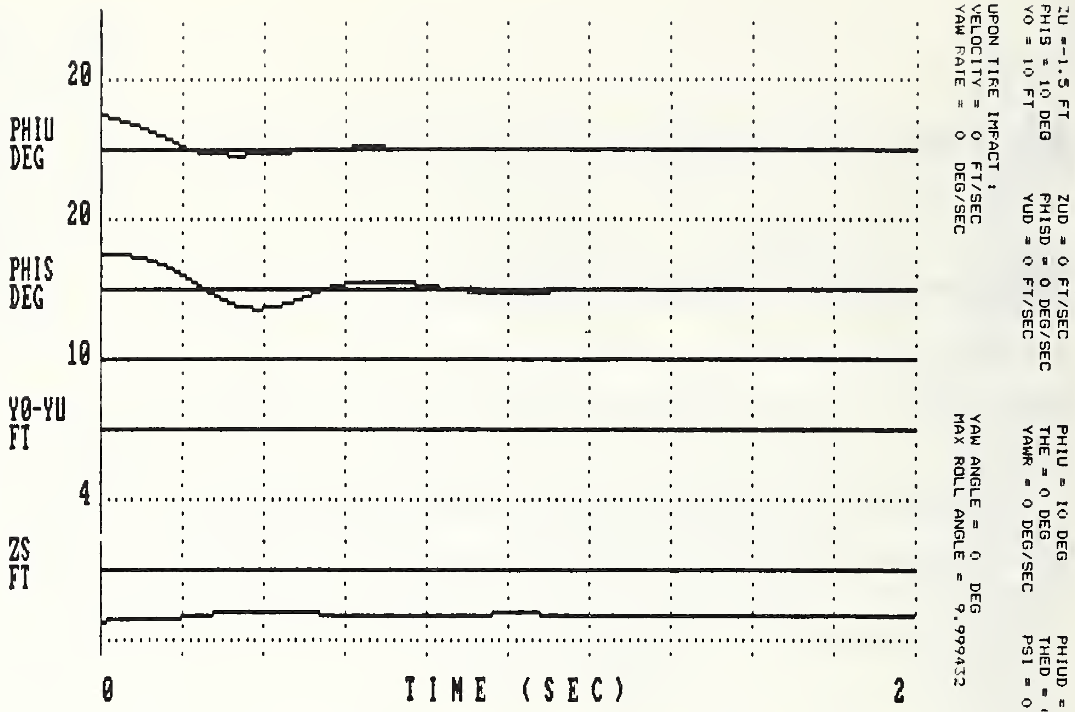
Cases 10-13 are a compilation of tests involving the yawing motion of the car. In Cases 10 and 11 (Figs. 8a and 8b) the car was given only an initial yaw rate. The purpose for these cases was to show that the yaw rate decreased to zero while the yaw angle approaches a constant value. This test was run for both positive and negative yaw rates, and in both cases the results were found to be dynamically consistent with expected real world behavior. The other yawing condition considered was for a car sliding at an initial yaw angle. When the car came to a stop the yaw angle should have remained the same. As can be seen in Figs. 8c and 8d this was indeed the case for both positive and negative yaw angles.



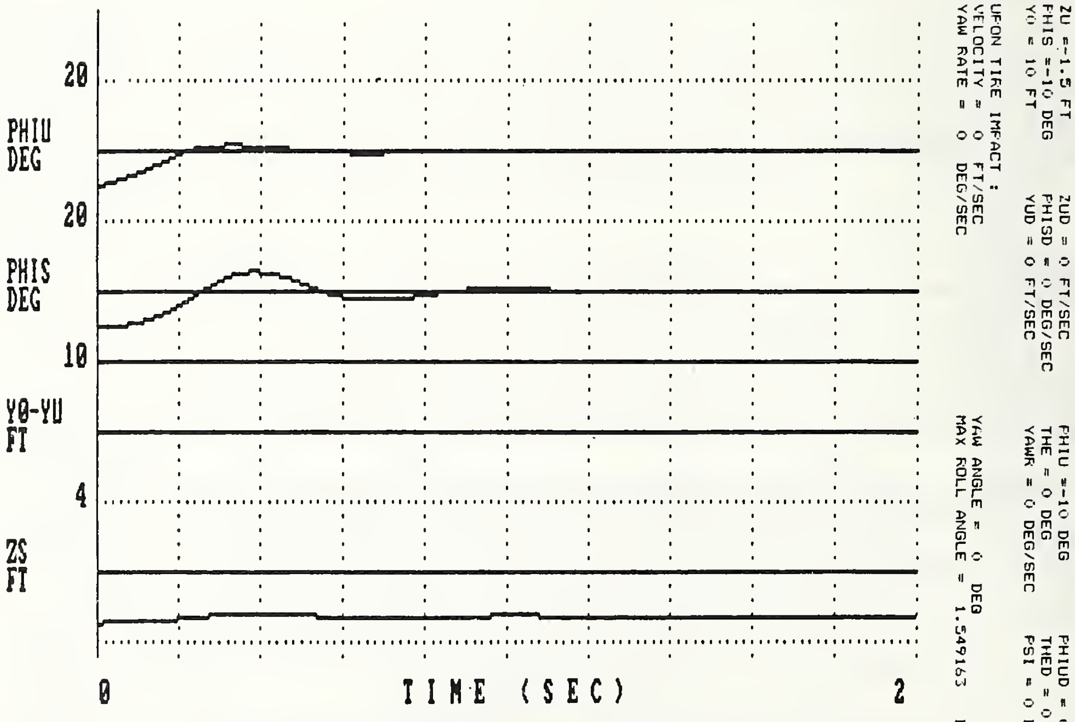
a) Initial Positive Sprung Mass Roll Angle Perturbation

b) Initial Negative Sprung Mass Roll Angle Perturbation

Figure 6. Test Cases for Both Unsprung and Sprung Mass Roll Perturbations

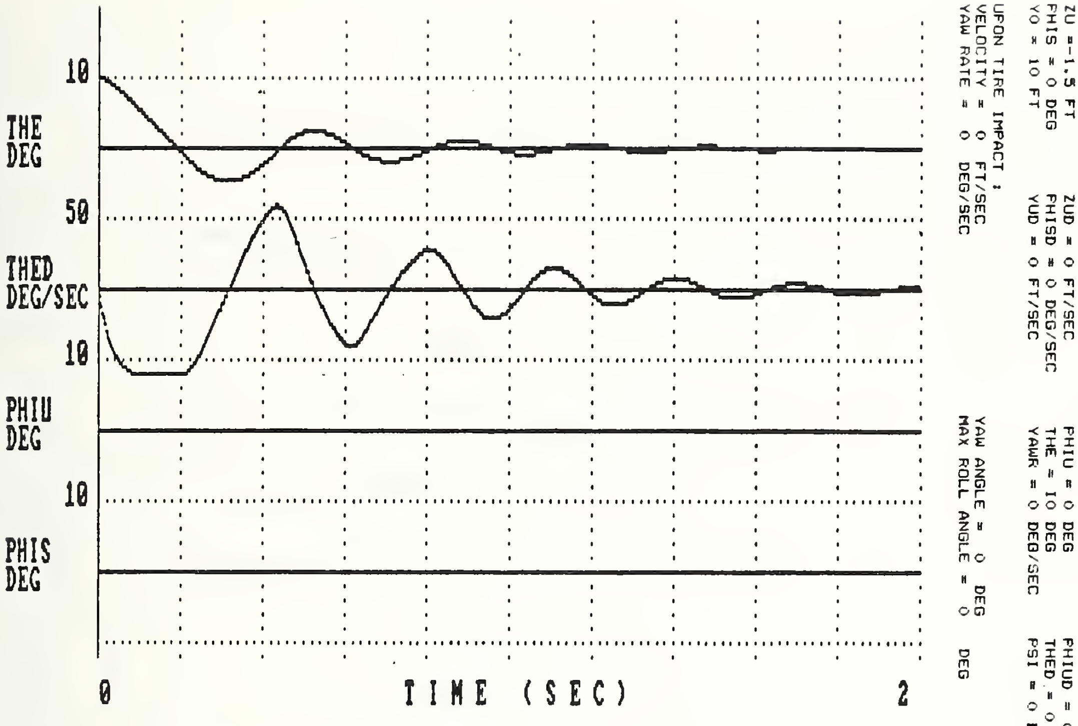


c) Initial Positive Unsprung Mass Roll Angle Perturbation

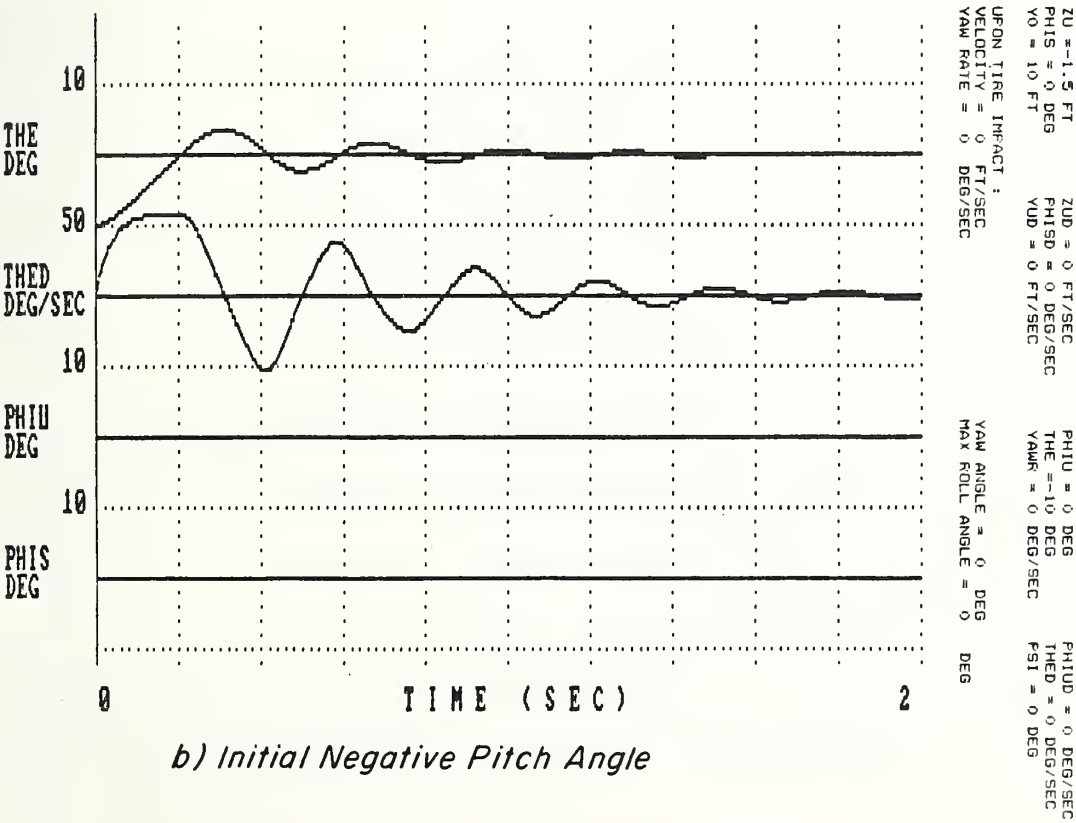


d) Initial Negative Unsprung Mass Roll Angle Perturbation

Figure 6. (Concluded)

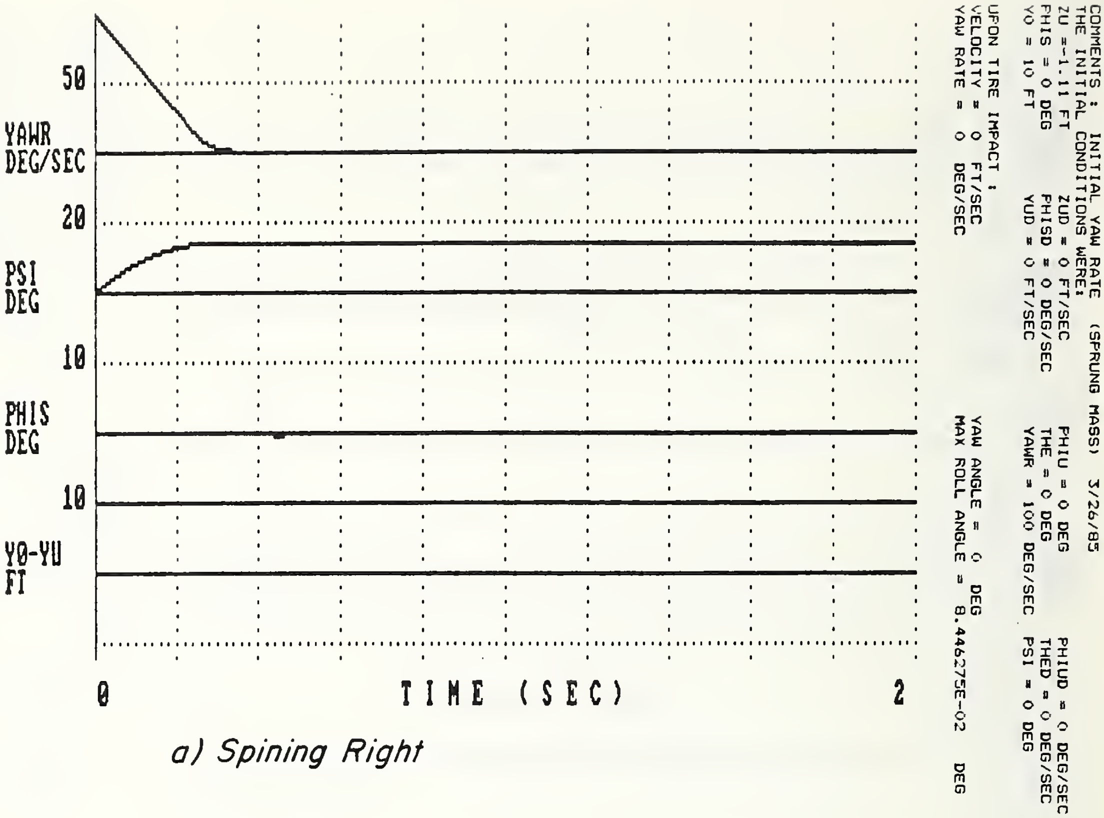


a) Initial Positive Pitch Angle

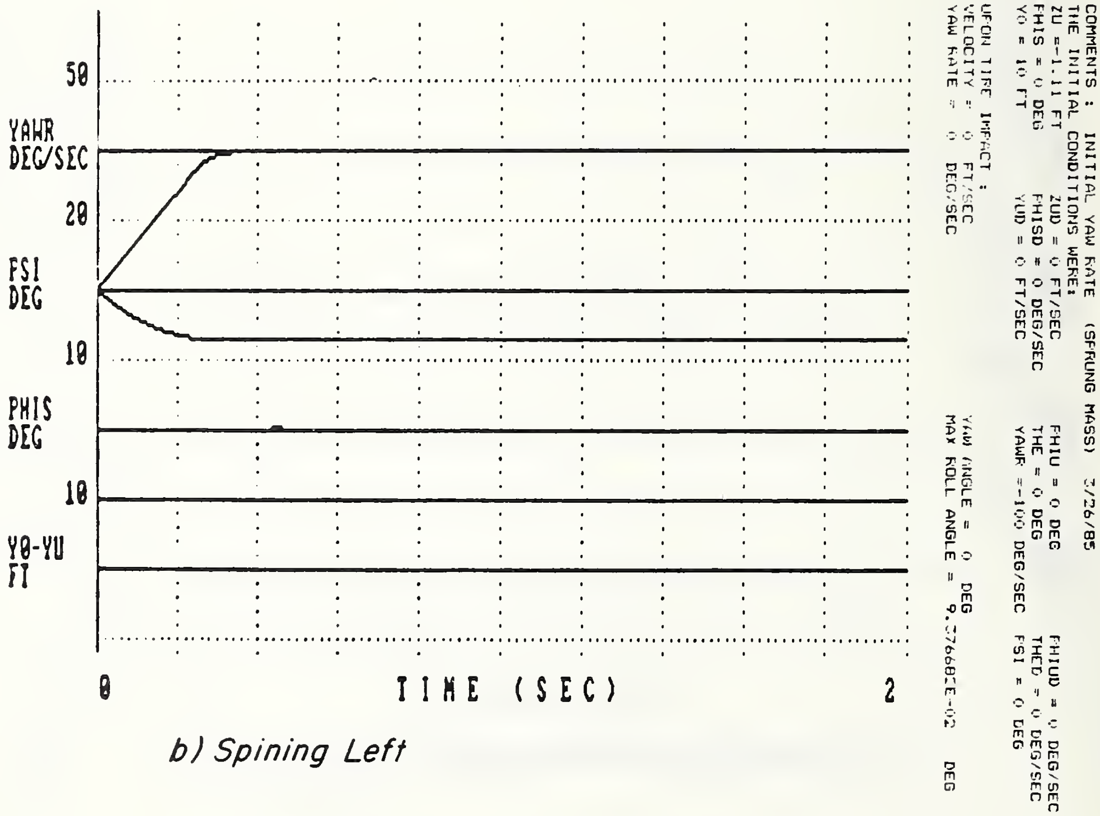


b) Initial Negative Pitch Angle

Figure 7. Test Cases for Pitch Degree-of-Freedom

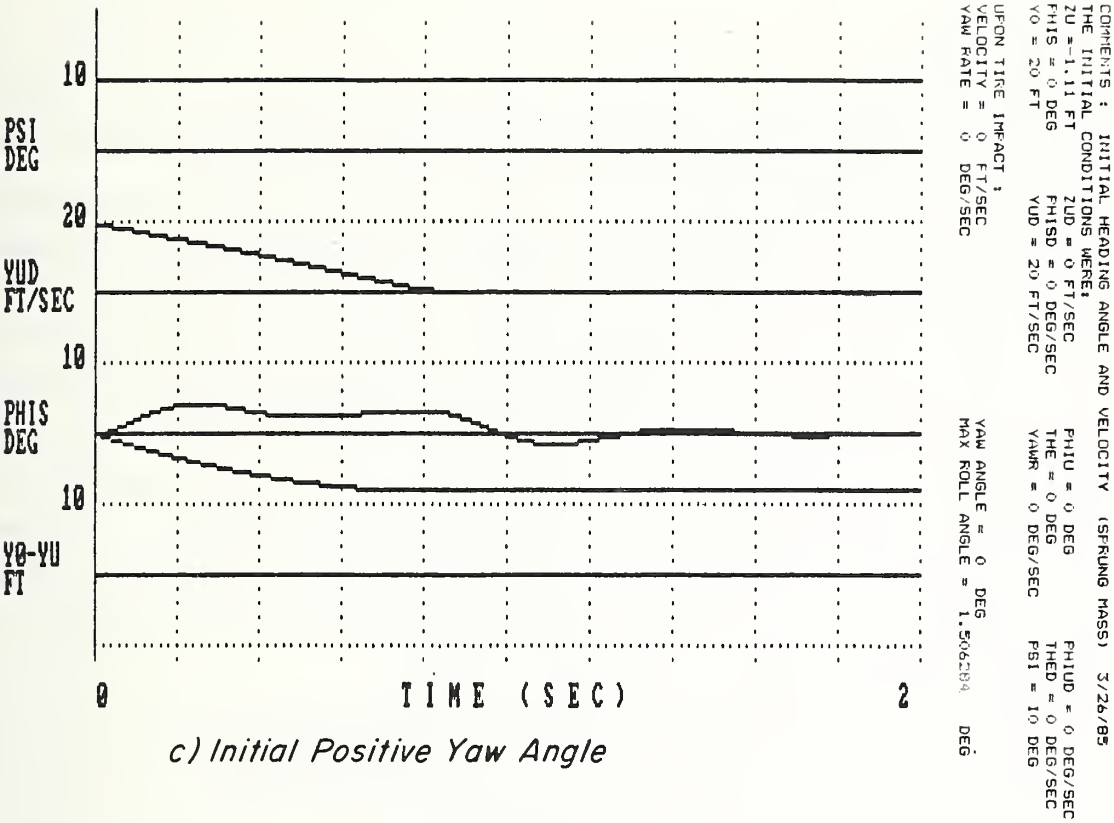


a) Spining Right

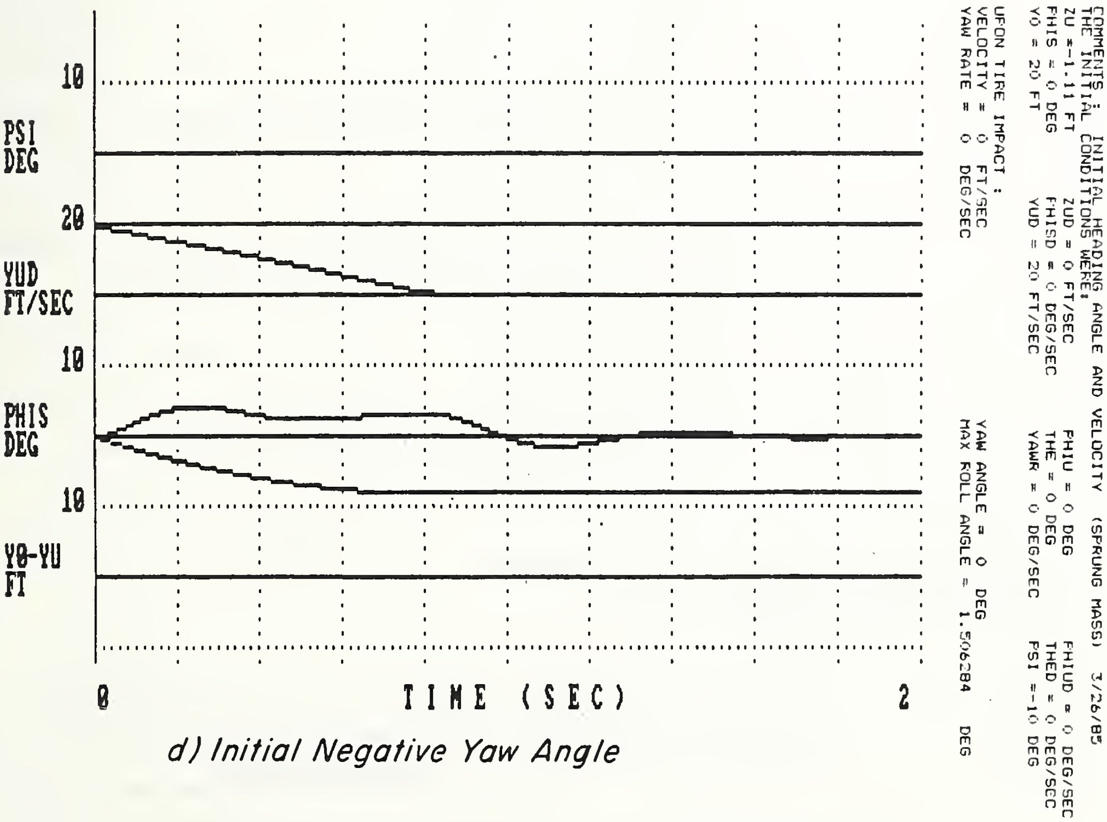


b) Spining Left

Figure 8. Test Cases for the Yaw Degree-of-Freedom



c) Initial Positive Yaw Angle



d) Initial Negative Yaw Angle

Figure 8. (Concluded)

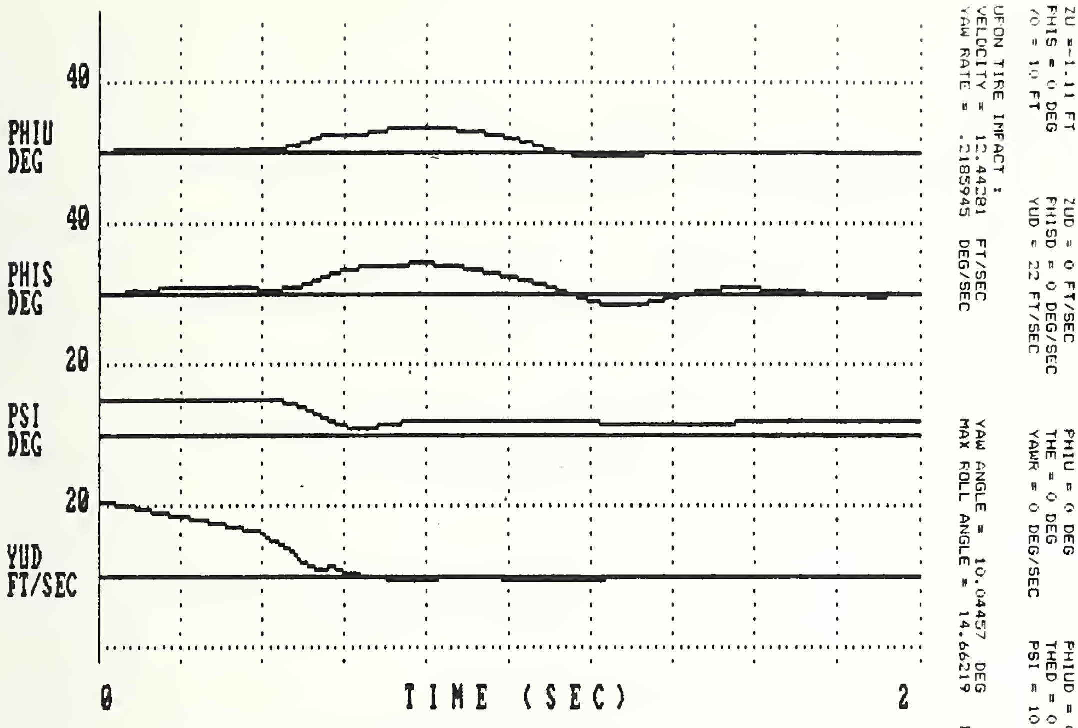
6. Curb Impact

Cases 14-17 (Fig. 9) represent initial conditions set up so that the car, traveling at some velocity and some initial heading angle, impacts the curb. Cases 14 and 15 were run with a non-symmetric car (distance from the center of gravity to the front and rear axles was not the same), whereas Cases 16 and 17 are for a symmetric car (distance from the center of gravity to the front and rear axles was equal). For the non-symmetrical case when the car impacts the curb from both positive and negative heading angles (same magnitude in each case) there will be some minor differences due to the non-symmetrical conditions. This can be seen in Figs. 9a and 9b. For symmetrical cases the vehicle response should be the same regardless of which direction the heading angle acts. This can be seen in Figs. 9c and 9d.

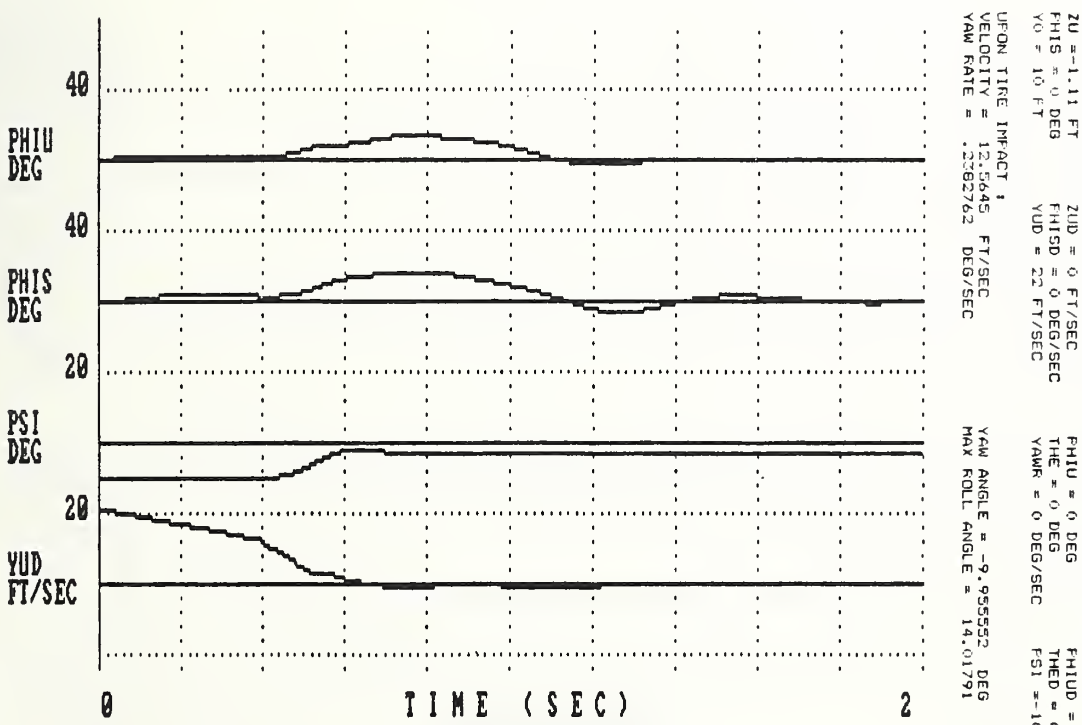
In Cases 18 and 19 (Fig. 10) the car slides into the curb with only an initial velocity. Figure 10a represents a case were the car did not roll over. This indicates that the impact velocity was not sufficient enough to tip the car, and a higher velocity is needed. Figure 10b once again represents a case where the car did not tip over. However, Fig. 10b was obtained using the program's iteration method to determine the tip over velocity. Near the top of Fig. 10b is the impact velocity, this velocity (which is slightly greater than that shown in Fig. 10a) is the maximum velocity at which the car may impact the curb and not roll-over. This brings us to Fig. 10c which represents the car tipping over. The impact velocity for this case is slightly greater than that from Fig. 10b, yet the car did roll over. This shows that the iteration method works to approximately ±0.1 ft/sec. The tip over velocities shown in Fig. 10 are in the range of that expected.

D. TEST CASES FOR TRIP (MODEL WITHOUT SEPARATE SPRUNG MASS)

Before the final version of the program was developed and tested a less complex car model was developed. This model did not include the sprung mass degree-of-freedom. Instead the earlier program was designed using only the unsprung mass with a center of gravity height equivalent

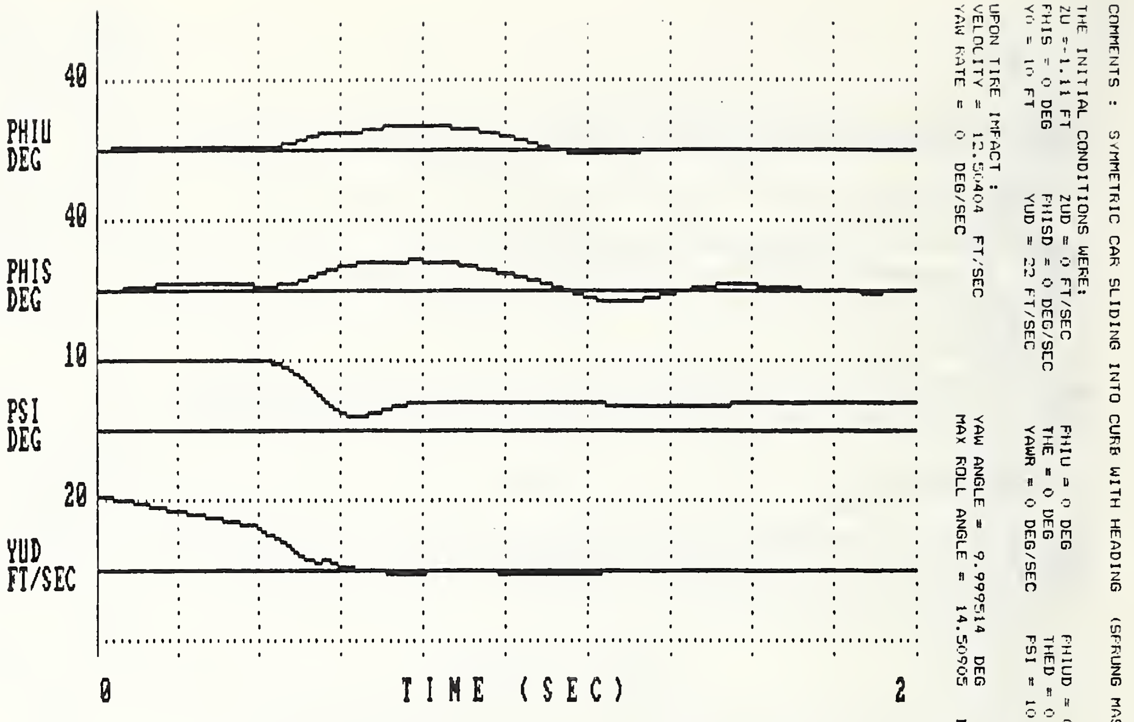


a) Non-Symmetric (yz plane) With Positive Heading Angle

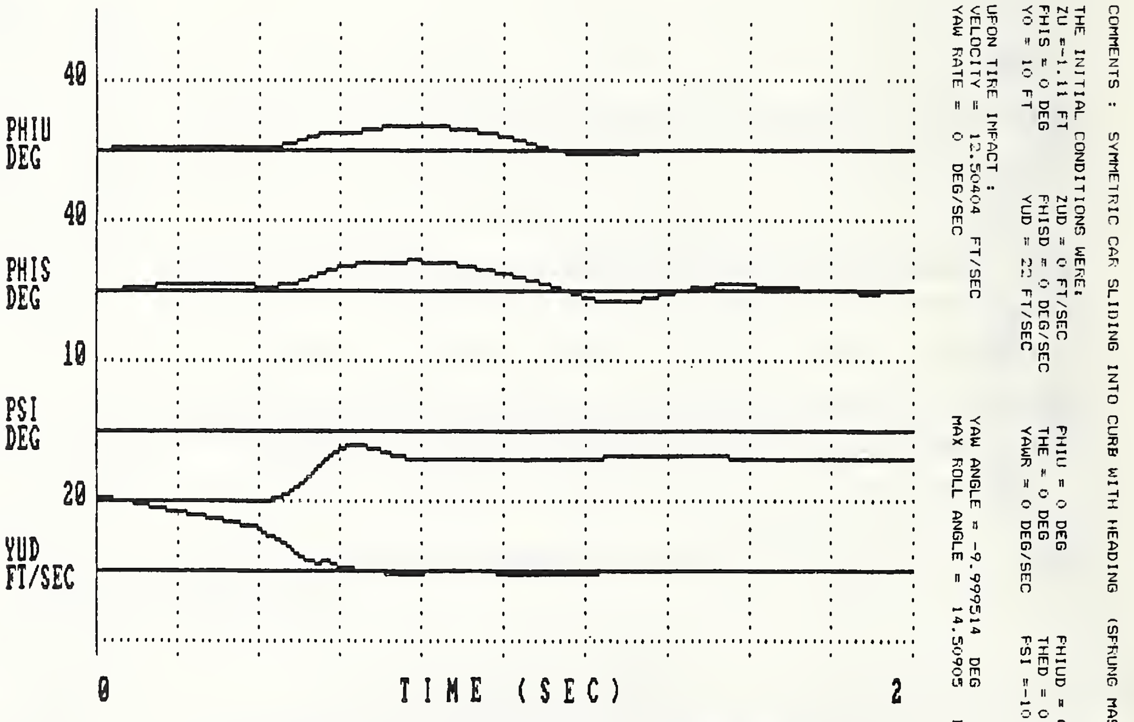


b) Non-Symmetric (yz plane) With Negative Heading Angle

Figure 9. Test Case for a Car Impacting Curb with a Heading Angle

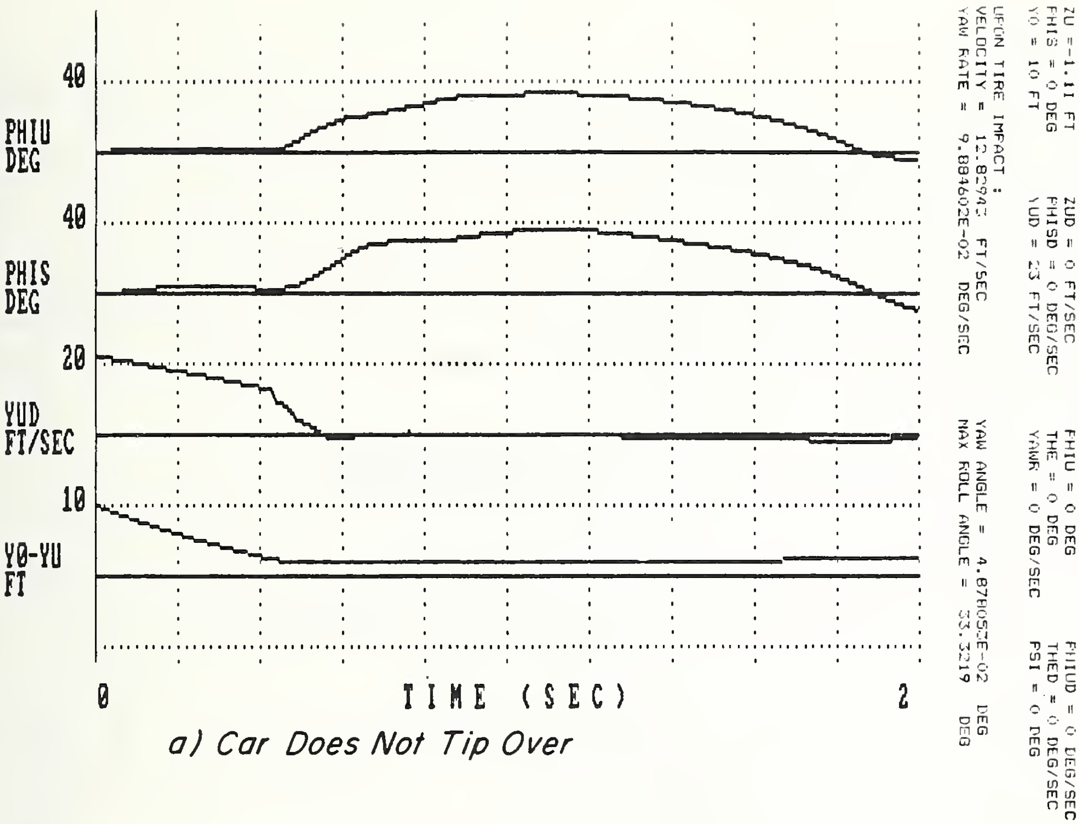


c) Symmetric (yz plane) With Positive Heading Angle

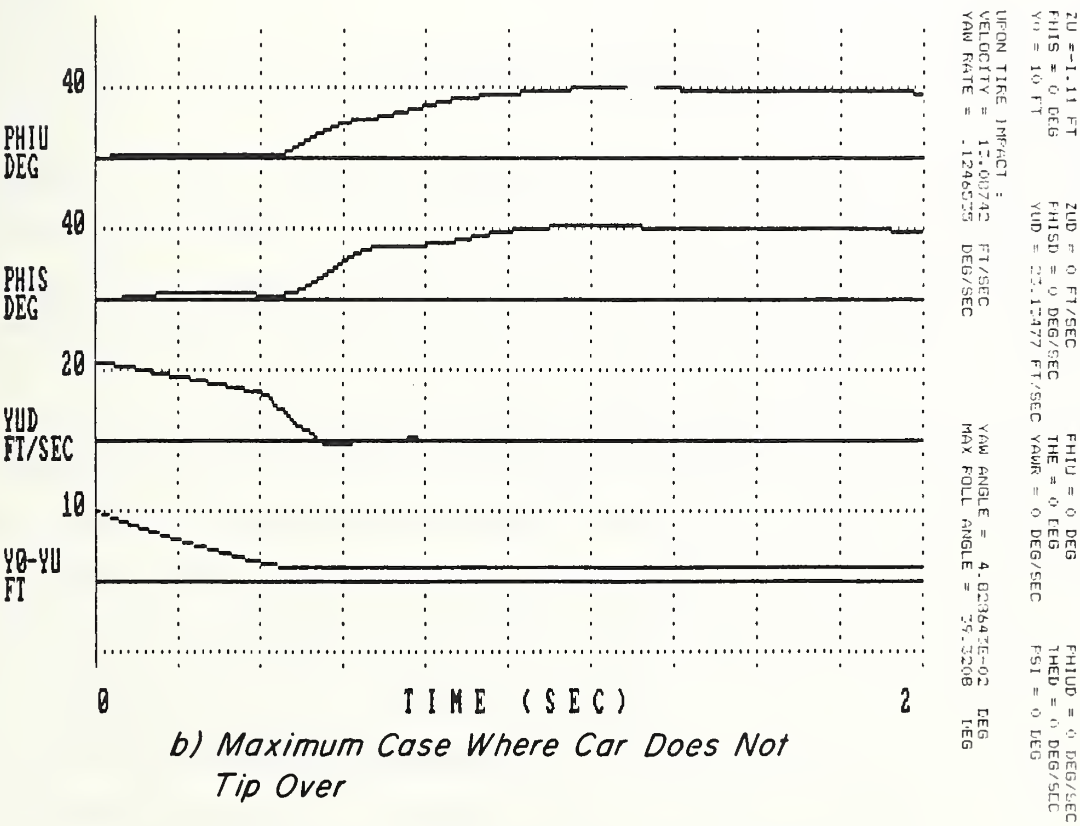


d) Symmetric (yz plane) With Negative Heading Angle

Figure 9. (Concluded)

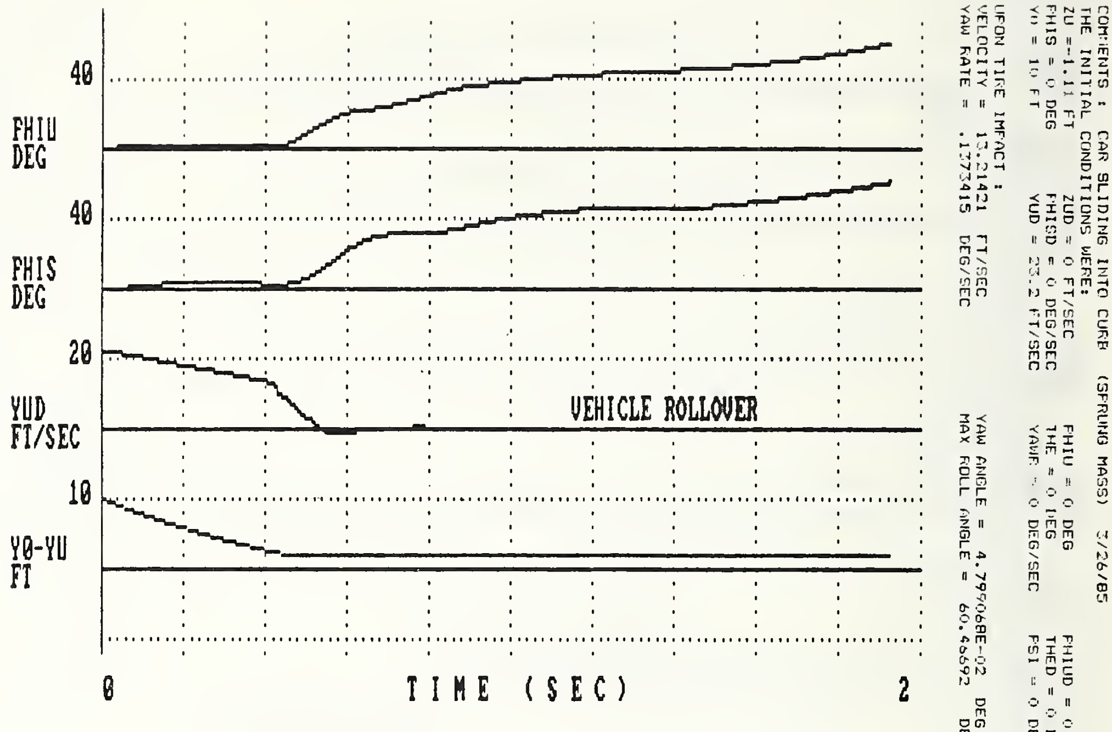


a) Car Does Not Tip Over



b) Maximum Case Where Car Does Not Tip Over

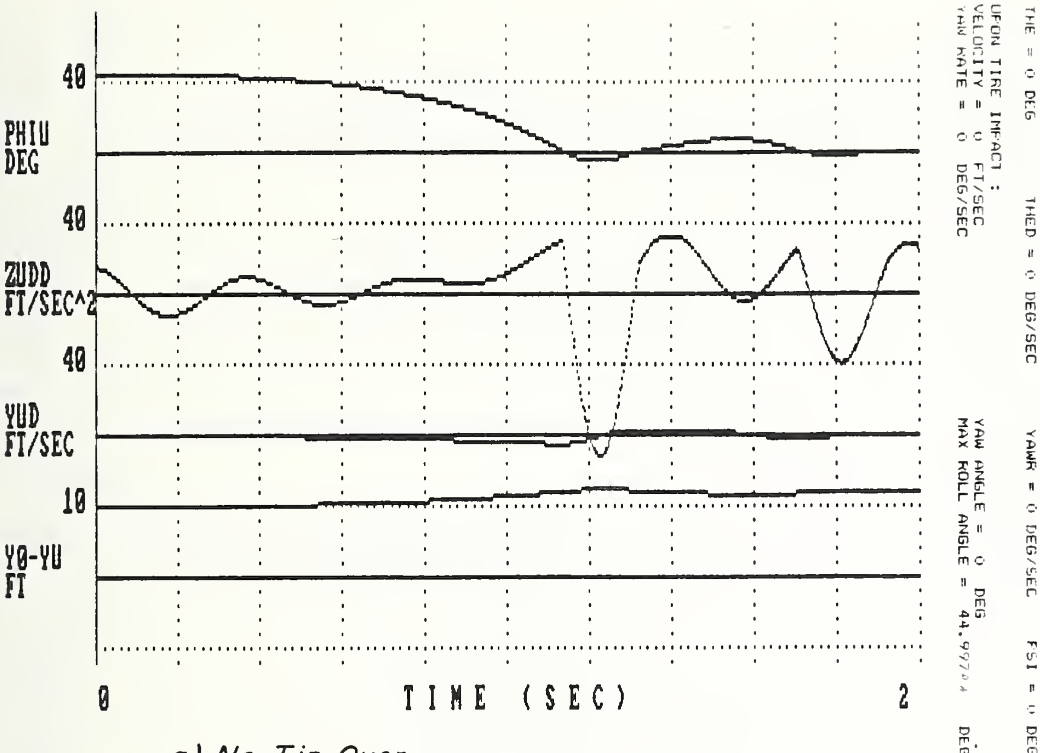
Figure 10. Test Case for Car with No Heading Impacting Curb



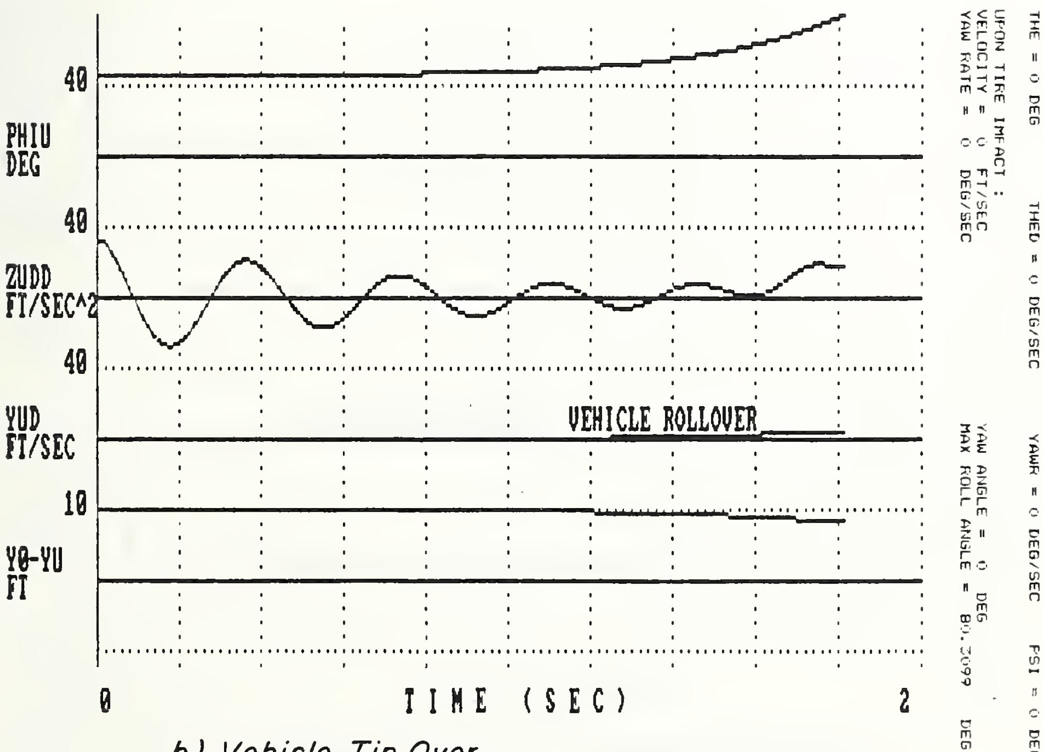
c) Car Tip Over

Figure 10. (Concluded)

to that of the sprung and unsprung masses together. Once the sprung mass program was finally developed it was useful to compare the two programs. Figures 11-13 represents the final six test cases that were run. Figures 11a and 11b show that the tip over angle for the unsprung mass program (TRIP) was between 45 and 46 deg, which was expected. For the sprung mass program (SPTRIP) the suspension springs were stiffened and Figs. 12a and 12b show a tip over angle between 49 and 50 deg. The difference in tip over angle is attributed to the fact that although the suspension springs were stiffened, it was impossible to make them completely rigid and therefore they deflected and caused varying forces. It should be noted here that the tip over angle from Figs. 12a and 12b is not the same as that in Fig. 10 due to the fact that when the car impacts with the curb the axle is crushed and the half track width is shortened, therefore making tip over easier. In the cases shown in Figs. 11-12 the left wheels were lifted off the ground and released,

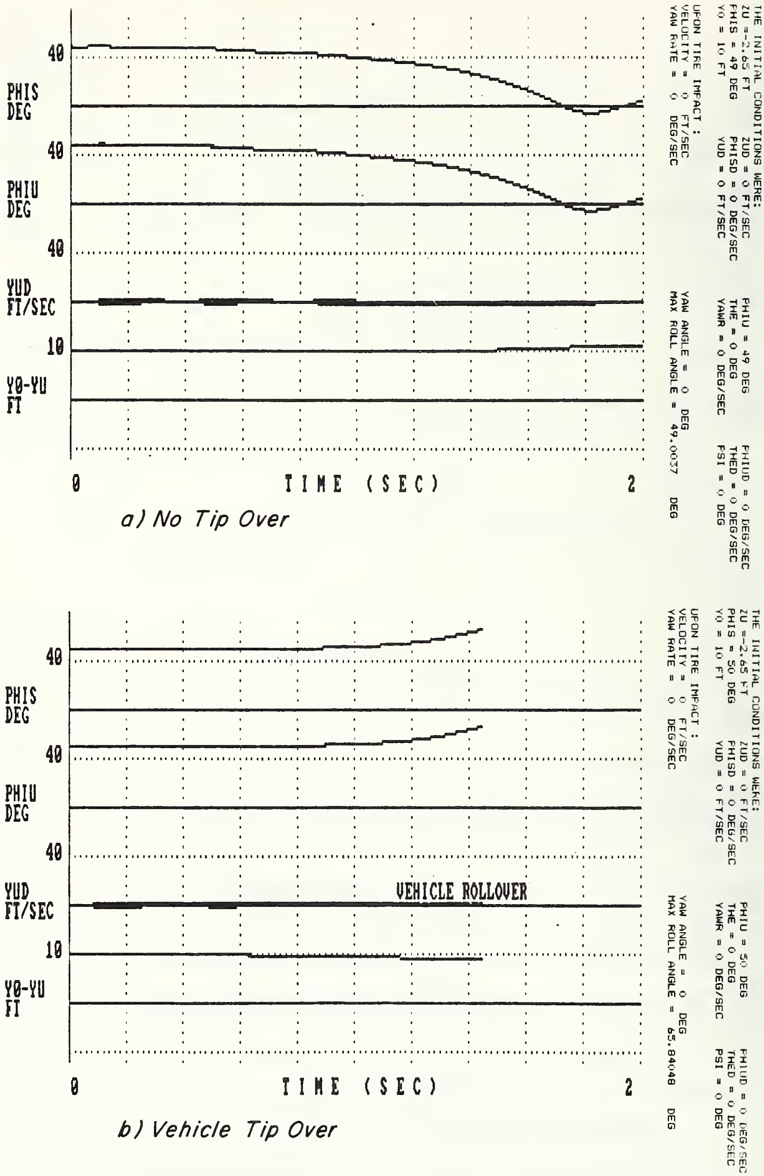


a) No Tip Over



b) Vehicle Tip Over

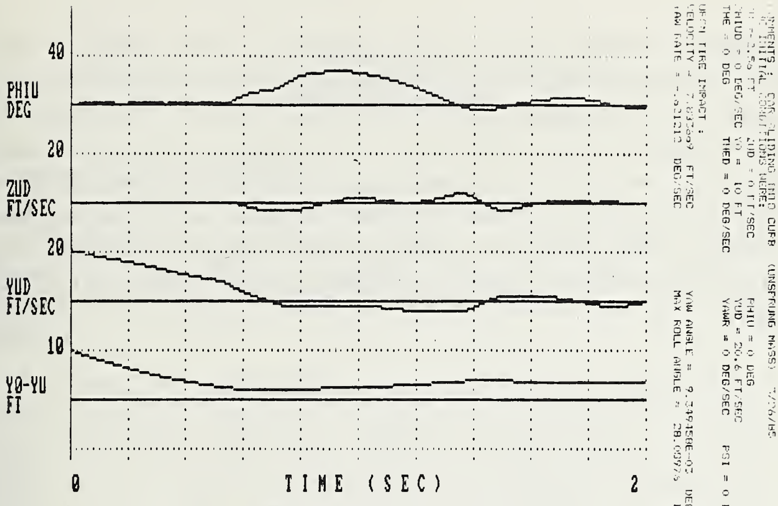
Figure 11. Test Case for the Static Tip Over Condition Using the Unsprung Mass (TRIP) Program



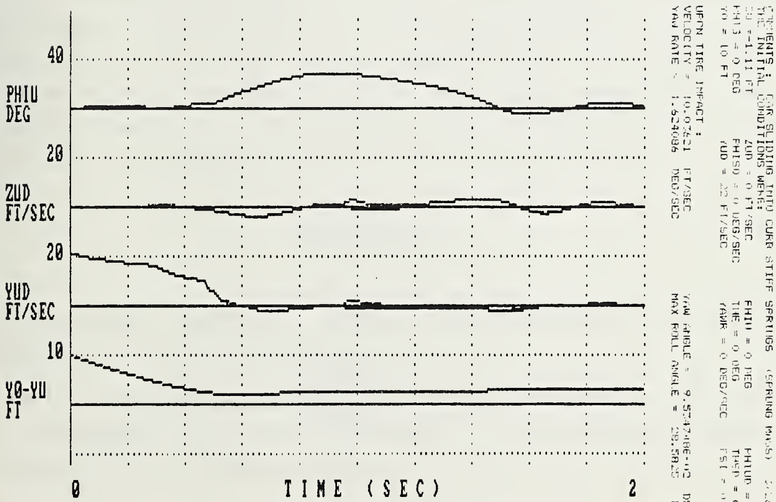
a) No Tip Over

b) Vehicle Tip Over

Figure 12. Test Case for the Static Tip Over Condition Using the Sprung Mass (SPTRIP) Program



a) Car Sliding Into Curb Using TRIP



b) Car Sliding Into Curb Using SPTRIP

Figure 13. Comparison Between the Unsprung Mass (TRIP) and Sprung Mass (SPTRIP) Programs

therefore the axles did not crush and tip over was more difficult. The final two cases (Figs. 13a and 13b) are provided to show the similarity between the two programs when the car impacts the curb. Both Figs. 13a and 13b reach the same roll angle but with different impact velocities. It can be seen that for the sprung mass program (Fig. 13b) a greater velocity was needed to produce the same roll angle as the unsprung mass program. These results show that the two programs are similar, and adding the sprung mass degrees-of-freedom did not adversly affect the model.

SECTION III

USER INSTRUCTIONS

A. INSTALLATION AND OPERATION

This program was designed to operate on an IBM© personal computer (or any compatible system). The disk is set up for easy operation so that even with little or no computer experience the program is easily accessible.

By placing the program diskette in drive A (the left disk drive) and either turning the computer on or booting the system, i.e., (simultaneously depressing the control Ctrl, alternate Alt, and delete Del keys) the computer will startup, load the system, and install the graphics routine. From here the user must decide which form of the program will be used.

The original disk contains a compiled version of both the unsprung mass program (TRIP) and the sprung mass program (SPTRIP). These compiled versions will only work with computers that have an 8087 math coprocessor chip. For this reason the Basic source code has also been included on the disk so that users may compile the program to suit their needs. The two compiled versions are filed under the names:

TRIP87.EXE
SPTRIP87.EXE

When the prompt appears (A>) typing in the appropriate file name and entering it will execute the program.

Finally the capital lock Caps Lock key must be activated so that capital letters appear when keys are depressed. If not, when the program is running it will not execute properly.

B. USER INPUTS AND PLOTTING OUTPUT

The initial conditions that the user must enter into the computer during program operation will now be discussed. The following pages show the actual input questions (underlined terms indicate user inputs), that will be asked during program operation. These will be used as a reference when discussing each individually. The following discussion will focus on the sprung mass program (SPTRIR). The inputs for the unsprung mass program (TRIP) are similar with the exception that they do not contain the sprung mass degree of freedom inputs and options.

User/computer dialog is shown explicitly in Table 1.

The first prompt in Table 1 instructs the user to enter the name of the file that is to be used during program execution. The user is reminded to use both a disk drive specifier (A:, B:, etc.) and extension (.75, .BAS, etc.) if they apply.

The second Table 1 prompt allows the user to either iterate to the vehicles tip over condition using velocity as the variable, or to look at one particular set of conditions at a time.

The third Table 1 prompt is dependent on the form of the previous input. As was mentioned earlier if the inputs are not in capital letters the program will not function properly. If the answer to question 2 was input using capital letters the program will bypass this section and proceed. If the answer was input using lower case letters this section will prompt the user to first activate the capital lock [Caps Lock] key and then reenter the answer.

The fourth Table 1 prompt designates which four variables the user would like to see on the plot, and what the scaling for each will be. A list of variables will appear with a short explanation of what each variable represents. From the list, four variables are choosen and entered one at a time with their desired scale (e.g., <u>PHIS,40</u> or <u>YUD,20</u>, etc.).

TABLE 1. USER/COMPUTER DIALOG (UNDERLINED TERMS INDICATE USER INPUTS)

1. ENTER THE DESIRED FILE NAME
(INCLUDE DRIVE SPECIFIER IF NEEDED)
? A:SPNOVA.75

2. WOULD YOU LIKE THE PROGRAM TO ITERATE TO
THE TIP OVER VELOCITY (Y OR N)?
? n

3. PLEASE, DEPRESS THE CAPS LOCK KEY (RIGHT OF THE SPACE BAR)
ONE TIME AND THEN REENTER YOUR REPLY TO THE ABOVE
? N

4. PLOTTING VARIABLE SELECTION:

PHIS	-	THE SPRUNG MASS ROLL ANGLE
PHISD	-	THE SPRUNG MASS ROLL RATE
PHISDD	-	THE SPRUNG MASS ROLL ACCELERATION
PHIU	-	THE UNSPRUNG MASS ROLL ANGLE
PHIUD	-	THE UNSPRUNG MASS ROLL RATE
PHIUDD	-	THE UNSPRUNG MASS ROLL ACCELERATION
PSI	-	THE YAW ANGLE AS THE CAR APPROACHES THE CURB
THE	-	THE CAR'S PITCH ANGLE
THED	-	THE CAR'S PITCH RATE
THEDD	-	THE CAR'S PITCH ACCELERATION
YAWR	-	THE RATE OF YAW AS THE CAR APPROACHES THE CURB
YAWRD	-	THE YAW ACCELERATION AS THE CAR APPROACHES THE CURB
YO-YU	-	THE c.g.'s DISTANCE FROM CURB
YU	-	THE c.g.'s POSITION WITH RESPECT TO IT'S INITIAL CON
YUD	-	THE c.g.'s LATERAL VELOCITY
YUDD	-	THE c.g.'s LATERAL ACCELERATION
ZU	-	THE c.g.'s VERTICAL POSITION WITH RESPECT TO THE GROUND
ZUD	-	THE c.g.'s VERTICAL VELOCITY
ZUDD	-	THE c.g.'s VERTICAL ACCELERATION
DELZU	-	THE CHANGE IN ZU FROM ITS STATIC POSITION

ENTER 4 VARIABLES AND THEIR SCALES ONE AT A TIME (i.e., PHIS,40)
? PHIS,40
? PHIU,40
? YUD,20
? YO-YU,10

TABLE 1. (CONCLUDED)

5. INITIAL CONDITION SPECIFICATION FOR VARIABLES:

```
ENTER : ZU (FT), ZUD (FT/SEC), PHIU (DEG), PHIUD (DEG/SEC)
? -1.11,0,0,0


ENTER : PHIS (DEG), PHISD (DEG/SEC), THE (DEG), THED (DEG/SEC)
? 0,0,0,0


ENTER : YO (FT), YUD (FT/SEC), PSI (DEG), YAWR (DEG/SEC)
? 10,22;0,0
```

6. COMPUTATION TIME INCREMENT AND TIME SPAN:

```
ENTER THE DESIRED TIME INCREMENT (<=.0025)
? .0025


ENTER THE DESIRED TIME LIMIT (INTEGERS ONLY)
? 2


ENTER ONE LINE OF COMMENTS (PLEASE, NO COMMAS)?
? ANY LINE OF COMMENTS CAN GO IN HERE BUT NO COMMAS
```

The fifth set of prompts requests specification of the vehicle's initial conditions. There are several important things to remember when entering the initial conditions. The first is that Z_u (the unsprung mass center of gravity vertical distance, above the ground) should be negative and close to the trim value for the vehicle, and that it depends on the initial pitch and roll angles. Secondly Y_o (the initial perpendicular distance from the center of gravity to the curb) must start at least the distance of one-half the track width from the curb. Otherwise the vehicle will be past the curb at the start.

Due to the complexity of the program and the different dynamic modes it contains it was found to run best when time increments of 0.0025 and under are used. The rest of the initial vehicle conditions are user dependent and the only restriction is that they are entered in the specified units. The desired time limit refers to the maximum amount of simulated and plotted time that the user would like. This input must be input in seconds and only integer values should be used.

The final input question allows the user to input a line of comments that will appear on the plots. Due to the structure of the program, however, no commas may be used.

Once all of the inputs have been entered a grid will appear on the screen and the curves will be plotted. If the program is iterating, each iteration will produce a new set of time histories for the user to see. When the program is through running it will beep to alert the user that it is done. The program will automatically print out the line of comments, the initial conditions, and the conditions upon impact. At this point the user can either get a copy of the variable time histories or change the dynamic inputs or plotting variables. To obtain a copy of the time histories the user must simultaneously depress the shift $\boxed{\Uparrow}$ and print screen $\boxed{\text{Prt Sc *}}$ keys. After the print is done or before printing, depressing any key will return the user to the next section of the program.

C. REINITIALIZATION

This section of the program allows the user to change any of the initial dynamic inputs (Table 1, prompt 5), and (or) the plotting variables (Table 1, prompt 4).

The program will first prompt the user and ask if any of the initial dynamic variables are to be changed, Table 2, prompt 1. If the user's response is Y (Yes), the program will list the variables that may be changed and then prompt (Table 2, prompt 2) the user to enter the variable name, followed by a comma, and then the new value for that variable (e.g., YUD, 30). After the change is entered the program will prompt the user for another change. This process continues until all changes are made. At this point, (or any other time) when the program prompts for the next change, the user may continue by entering a Q , followed by a comma (e.g., Q,). The program will now proceed to the section that allows the user to change the plotting variables. It should be noted that entering the N (No) option when the program asks if any dynamic variables are to be changed (Table 2, prompt 2), will automatically take the user to the section that allows the plotting variables to be changed.

The program will now prompt the user and ask if any of the plotting variables will be changed, (Table 2, prompt 3). If the user's response is Y (Yes), the program will list all of the possible plotting variables. The user may now change the plotting variables, (Table 2, prompt 4) in the same manner as was shown in Table 1, prompt 4. It should be noted that if the user decides to change any plotting variable, four variables must be input not just one. After these four variables and their scales are input the program will automatically plot the new time histories.

Finally, a N (No) response to prompt 3 will cause one of two events to occur. If prompt 1 is yes and prompt 3 is no, the program will plot the new time histories using the previous plotting variables. If prompt 1 is no and prompt 3 is no the program will cease execution.

TABLE 2. CHANGING INITIAL INPUTS (UNDERLINED TERMS INDICATE USER INPUTS)

1. WOULD YOU LIKE TO CHANGE ANY OF THE INITIAL DYNAMIC VARIABLES (Y OR N)?
   ?Y

2. YOU MAY CHANGE ANY OF THE VARIABLES LISTED BELOW:

ZU	ZUD
PHIU	PHIUD
PHIS	PHISD
THE	THED
YO	YUD
PSI	YAWR

   ENTER THE VARIABLE THAT YOU WOULD LIKE CHANGED, FOLLOWED BY THE NEW NUMERIC VALUE FOR THE VARIABLE (i.e., YUD, 25), OR ENTER (Q,) TO CONTINUE
   ?YUD,30

   ENTER ANOTHER VARIABLE TO CHANGE OR (Q,) TO CONTINUE
   ?Q,

3. WOULD YOU LIKE TO CHANGE THE PLOTTING VARIABLES (Y OR N)?
   ?Y

4.
PHIS	-	THE SPRUNG MASS ROLL ANGLE
PHISD	-	THE SPRUNG MASS ROLL RATE
PHISDD	-	THE SPRUNG MASS ROLL ACCELERATION
PHIU	-	THE UNSPRUNG MASS ROLL ANGLE
PHIUD	-	THE UNSPRUNG MASS ROLL RATE
PHIUDD	-	THE UNSPRUNG MASS ROLL ACCELERATION
PSI	-	THE YAW ANGLE AS THE CAR APPROACHES THE CURB
THE	-	THE CAR'S PITCH ANGLE
THED	-	THE CAR'S PITCH RATE

TABLE 2. (CONCLUDED)

THEDD	-	THE CAR'S PITCH ACCELERATION
YAWR	-	THE RATE OF YAW AS THE CAR APPROACHES THE CURB
YAWRD	-	THE YAW ACCELERATION AS THE CAR APPROACHES THE CURB
YO-YU	-	THE c.g.'s DISTANCE FROM CURB
YU	-	THE c.g.'s POSITION WITH RESPECT TO IT'S INITIAL CON.
YUD	-	THE c.g.'s LATERAL VELOCITY
YUDD	-	THE c.g.'s LATERAL ACCELERATION
ZU	-	THE c.g.'s VERTICAL POSITION WITH RESPECT TO THE GROUND
ZUD	-	THE c.g.'s VERTICAL VELOCITY
ZUDD	-	THE c.g.'s VERTICAL ACCELERATION
DELZU	-	THE CHANGE IN ZU FROM ITS STATIC POSITION

```
ENTER 4 VARIABLES AND THEIR SCALES ONE AT A TIME (i.e., PHIS,40)
? PHIU,40
? PHIS,40
? YUD,20
? YO-YU,10
```

REFERENCES

1. Jones, I. S., "Vehicle Stability Related to Frequency of Overturning for Different Models of Car," Proc. of the Australian Road Research Board, Volume 7, Part 5, 1974.

2. Allen, R. Wade, and Jeffrey R. Hogue, "GM X-Body Brake Lockup Problems: Summary Results from NHTSA/VRTC Tests," Systems Technology, Inc., WP-2246-2, Dec. 1984.

3. Allen, R. Wade, D. T. McRuer, and I. L. Ashkenas, "Preliminary Analysis of Driver Control Problems Associated with Rear Wheel Lockup," Systems Technology, Inc., WP-2246-1, Nov. 1984.

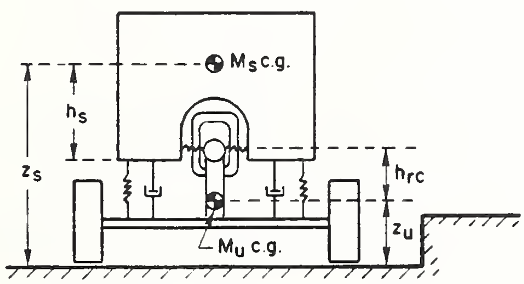
4. Allen, R. Wade, Jeffrey R. Hogue, and Zareh Parseghian, Manual Control of Unstable Systems, NASA CP-2428, May 1986.

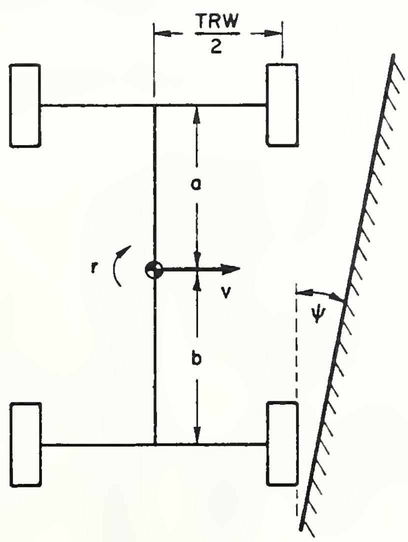
APPENDIX A

EQUATIONS OF MOTION FOR TRIPPED ROLLOVER ANALYSIS

1.0 GENERAL APPROACH AND OVERVIEW

The vehicle degrees of freedom include for the sprung and unsprung mass: roll (ϕ_s, ϕ_u), yaw (ψ), and pitch (θ) angles, lateral position (y), and vertical position (z). Constraints on the sprung relative to the unsprung roll angle include a torsional spring gradient with damping an bump stops. The tires include vertical compliance and lateral dynamic friction. The curb encounter will involve a force/deflection characteristic. The force and moment equations will be developed for both the sprung and unsprung masses. The following represents the vehicle model used:

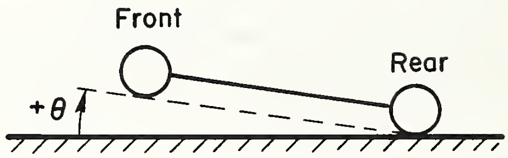




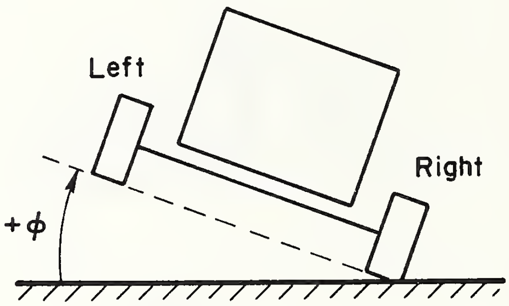
The axis system that is used is the standard aircraft body axis convention as shown:

where angles are measured as follows:

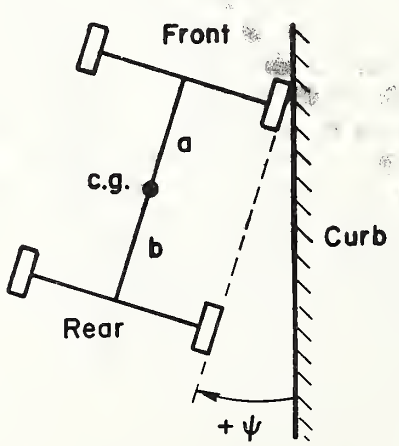
For pitch



For roll

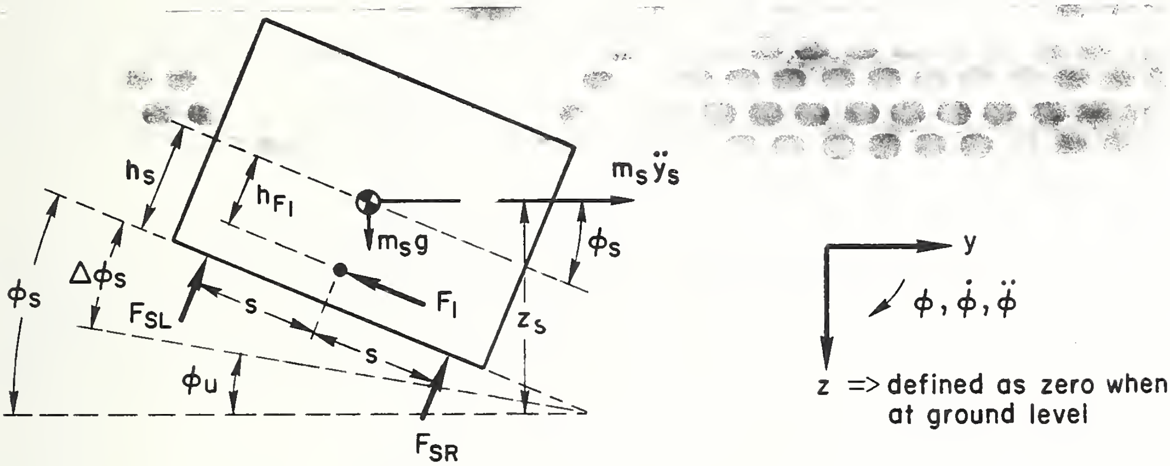


For yaw



1.1 SPRUNG MASS ROLL AXIS

By applying Newton's second law (F = ma) to the following free body diagram, both force equations and the moment equation for the sprung mass can be written.



1.1.1 Lateral Force Equation

$$m_s\ddot{y}_s = (F_{SL} + F_{SR}) \cdot \sin \phi_s - F_l \cdot \cos \phi_s$$

1.1.2 Vertical Force Equation

$$-m_s g + m_s\ddot{z}_s = -(F_{SL} + F_{SR}) \cdot \cos \phi_s - F_l \cdot \sin \phi_s$$

1.1.3 Moment Equation

$$I_s\ddot{\phi}_s = (F_{SL} - F_{SR}) \cdot S + F_l \cdot h_{F_l}$$

$$h_{F_l} = (y_s - y_u) \cos\phi_s + (z_u - z_s) \cos\phi_s - (h_r - h_u) \cos(\phi_s - \phi_u)$$

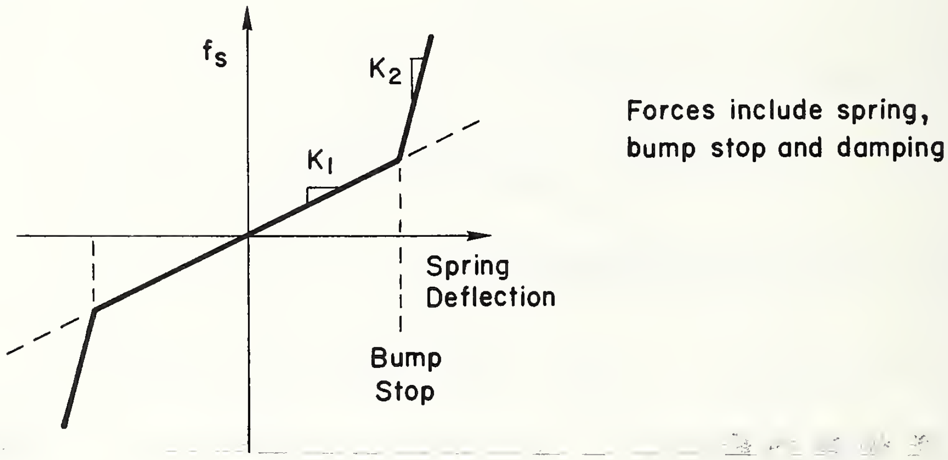
1.1.4 Suspension Forces

The vehicle's suspension system consists of both left and right suspension springs and bump stops. As the sprung mass and unsprung mass roll angles change, the suspension springs expand and compress causing suspension force changes. The bump stops prevent excessive tension or compression on the springs. The spring force equations can be written as:

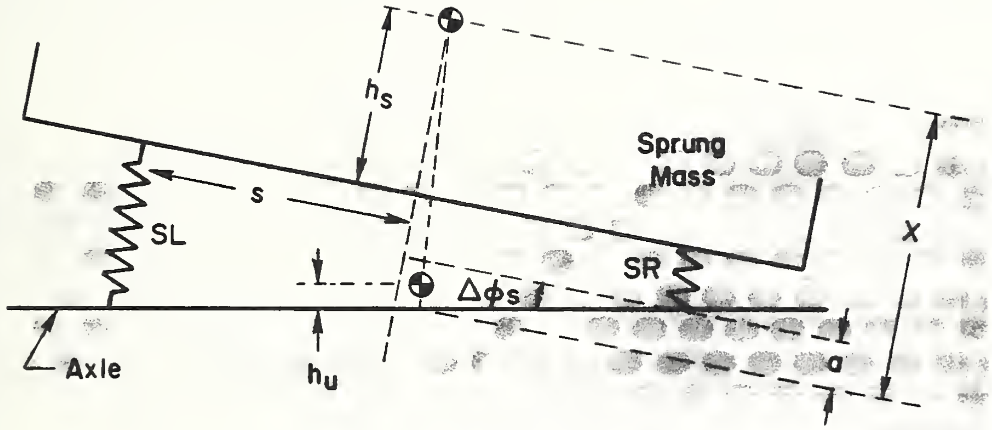
$$F_{SL} = \underbrace{K_1 \cdot SD_L + B_1 \cdot \dot{SD}_L}_{\text{Spring Force and Damping}} + \underbrace{K_2 \cdot BD_L + B_2 \cdot \dot{BD}_L}_{\text{Bump Stop Force and Damping}}$$

$$F_{SR} = \underbrace{K_1 \cdot SD_R + B_1 \cdot \dot{SD}_R}_{\text{Spring Force and Damping}} + \underbrace{K_2 \cdot BD_R + B_2 \cdot \dot{BD}_R}_{\text{Bump Stop Force and Damping}}$$

using:



The spring deflections can be found by subtracting the length of the spring at any instant in time from the unloaded spring length. The lengths of the springs at any instant in time can be found by the following:



Due to the bump stops, $\Delta\phi_s$ can not reach angles much greater than 8°, therefore it can be reasonably assumed that X is perpendicular to the axle. With this assumption X can be written as

$$X = \left[(z_s - z_u)^2 + (y_s - y_u)^2\right]^{1/2} + h_u$$

For convenience in future equations the following notation will be employed.

$$\Delta z = z_u - z_s$$

$$\dot{\Delta z} = \dot{z}_u - \dot{z}_s$$

$$\Delta y = y_s - y_u$$

$$\dot{\Delta y} = \dot{y}_s - \dot{y}_u$$

The right spring length can be written as

$$SR = \frac{X}{\cos \Delta\phi_s} - h_s - a$$

where

$$a = s \bullet \tan \Delta\phi_s$$

Therefore

$$SR = \frac{\left[\Delta z^2 + \Delta y^2\right]^{1/2} + h_u}{\cos \Delta\phi_s} - h_s - s \cdot \tan \Delta\phi_s$$

The left spring length can now be written as

$$SL = SR + 2s \cdot \tan \Delta\phi_s$$

Therefore

$$SL = \frac{\left[\Delta z^2 + \Delta y^2\right]^{1/2} + h_u}{\cos \Delta\phi_s} - h_s + s \cdot \tan \Delta\phi_s$$

From this the spring deflection terms can be written as

$$SD_L = \text{Spring Length} - SL$$

$$\dot{S}D_L = \dot{S}_L$$

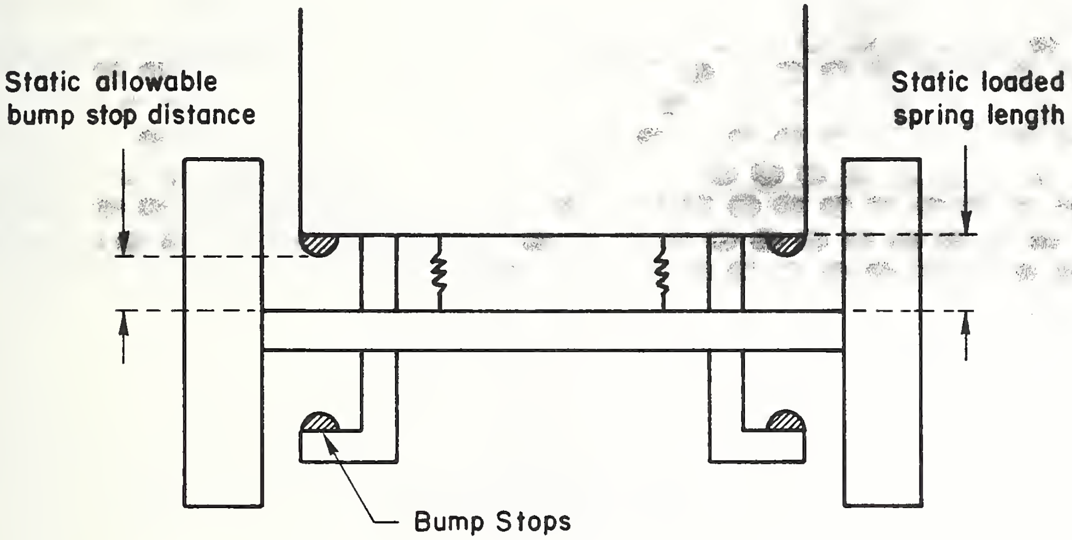
$$= -\frac{(\Delta z \cdot \dot{\Delta z} + \Delta y \cdot \dot{\Delta y})}{\cos \Delta\phi_s \, (\Delta z^2 + \Delta y^2)^{1/2}} - \frac{\dot{\Delta\phi}_s \left[s + [(\Delta z^2 + \Delta y^2)^{1/2} + h_u] \sin \Delta\phi_s\right]}{\cos^2 \Delta\phi_s}$$

and

$$SD_R = \text{Spring Length} - SR$$

$$\dot{S}D_R = -\frac{(\Delta z \cdot \dot{\Delta z} + \Delta y \cdot \dot{\Delta y})}{\cos \Delta\phi_s \, (\Delta z^2 + \Delta y^2)^{1/2}} - \frac{\dot{\Delta\phi}_s \left[[(\Delta z^2 + \Delta y^2)^{1/2} + h_u] \sin \Delta\phi_s - s\right]}{\cos^2 \Delta\phi_s}$$

The bump stop deflections are found directly from the spring lengths at any instant in time. They are determined by subtracting the spring length from the size of the bump stops. If the spring length is less than the bump stop size, then the axle is in contact with the bump stops. The size of the bump stops is determined from the following:



Bump Stop Size = Static Loaded Spring Length - Static Allowable Bump Stop Distance

Therefore

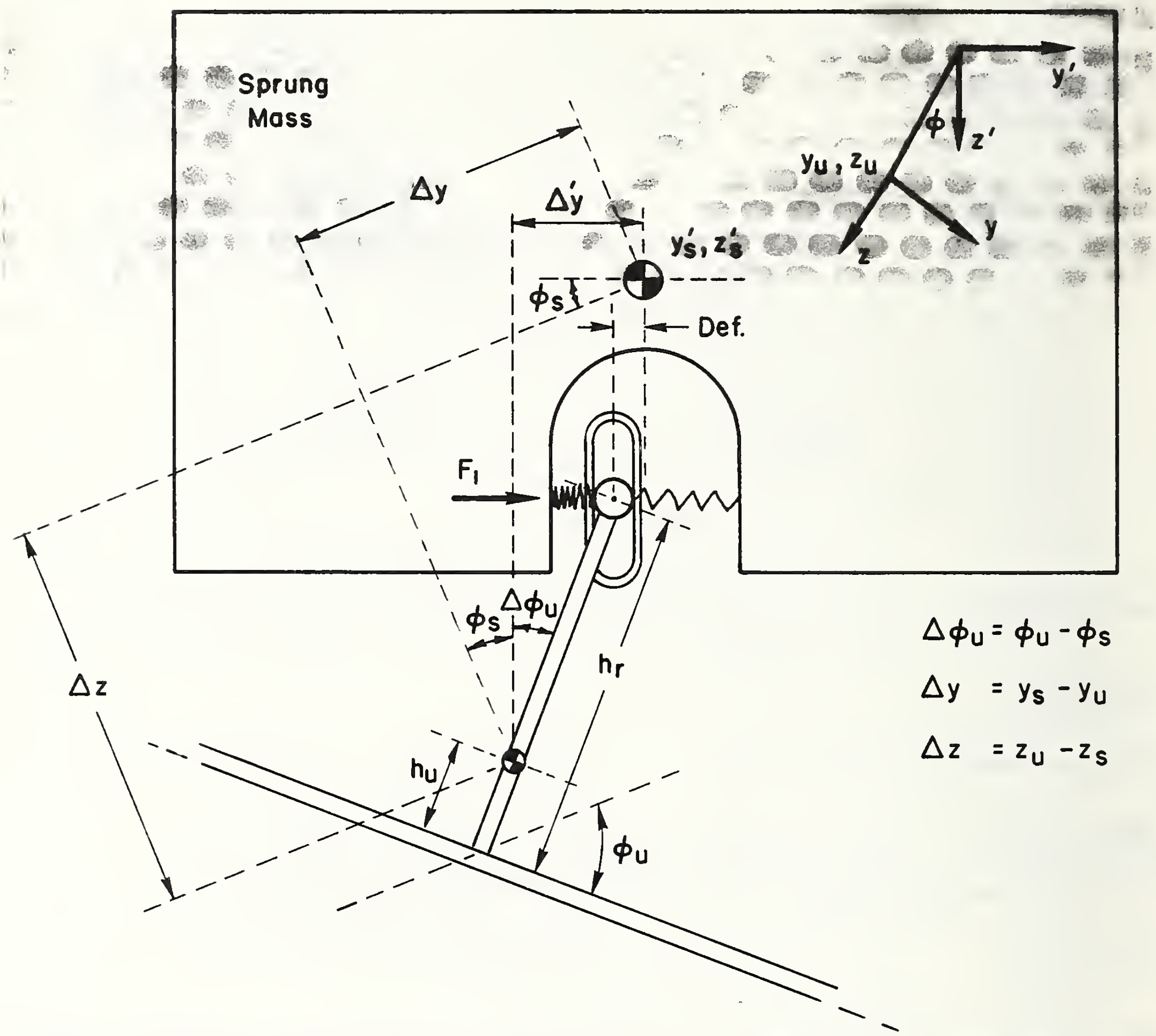
BD_L	=	Bump Stop Size - SL	for Bump Stop Size > SL
BD_L	=	0	for Bump Stop Size < SL
BD_R	=	Bump Stop Size - SR	for Bump Stop Size > SR
BD_R	=	0	for Bump Stop Size < SR

Since the bump stop sizes are essentially constant for any particular vehicle it follows that

$$\dot{BD}_L = \dot{SL}$$
$$\dot{BD}_R = \dot{SR} \qquad \text{for Bump Stop Size} > SL, SR$$

1.1.5 Lateral Restraining Force

The sprung and unsprung masses are connected together by a rubber bushing, therefore causing a lateral force between the two masses. The force can be approximated by a spring connection at this point.



The restraining force can be written

$$F_1 = K \cdot Def + B \cdot \dot{Def}$$

Using the above illustration Def can be determined as follows:

$$Def = \Delta y' - (h_r - h_u) \sin \Delta\phi_u$$

where

$$\Delta y' = [\Delta y - \Delta z \cdot \tan \phi_s] \cos \phi_s$$

$$\Delta y' = \Delta y \cdot \cos \phi_s - \Delta z \cdot \sin \phi_s$$

Therefore

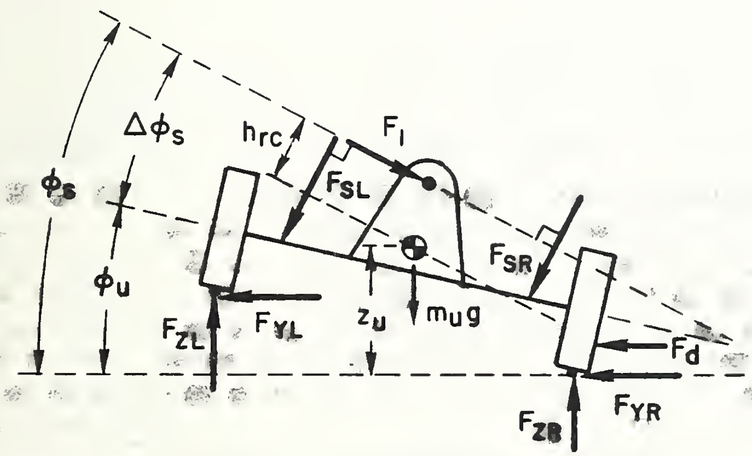
$$\text{Def} = \Delta y \cdot \cos \phi_s - \Delta z \cdot \sin \phi_s - (h_r - h_u) \sin \Delta\phi_u$$

and

$$\dot{\text{Def}} = \Delta\dot{y} \cdot \cos \phi_s - \Delta\dot{z} \cdot \sin \phi_s - \dot{\phi}_s [\Delta y \cdot \sin \phi_s + \Delta z \cdot \cos \phi_s]$$
$$- (h_r - h_u) \Delta\dot{\phi}_u \cdot \cos \Delta\phi_u$$

1.2 UNSPRUNG MASS ROLL AXIS

By applying Newton's second law to the following free body diagram, both force equations and the moment equation can be written for the unsprung mass.



$F_{YL} = F_{YLF} + F_{YLR}$

$F_{YR} = F_{YRF} + F_{YRR} + F_{dF} + F_{dR}$

z_u is motion of M_u downward

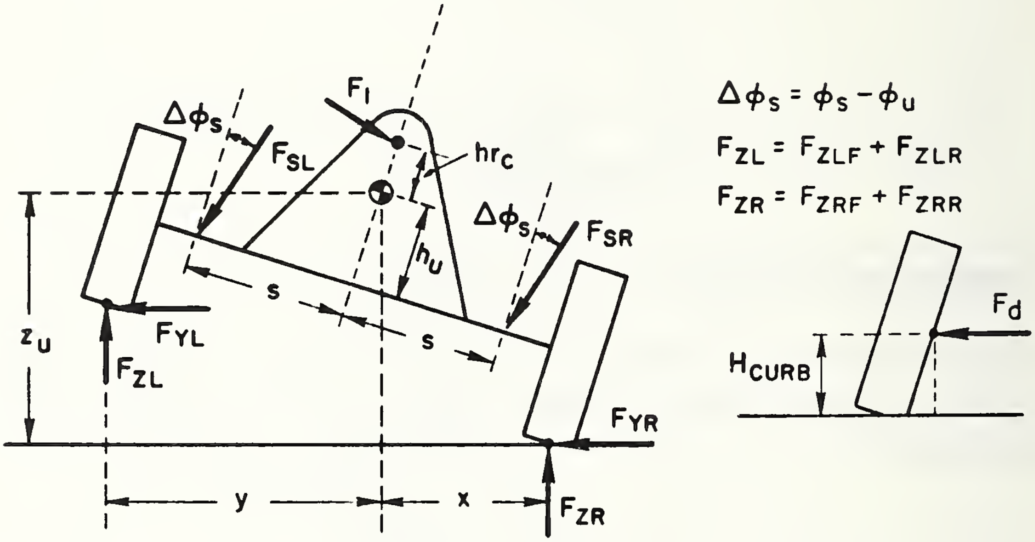
1.2.1 Lateral Force Equation

$$M_u \ddot{y}_u = F_l \cos \phi_s - (F_{SL} + F_{SR}) \sin \phi_s - F_{YR} - F_{YL} - F_d$$

1.2.2 Vertical Force Equation

$$- m_u g + m_u \ddot{z}_u = (F_{SL} + F_{SR}) \cos \phi_s + F_l \sin \phi_s - F_{ZL} - F_{ZR}$$

1.2.3 Moment Equation



When one or both tires are on the ground the moment arm for the tire sliding forces (F_{YR} ; F_{YL}) is just simply z_u. When the car comes in contact with the curb the moment arm for the curb forces (F_d) is simply $z_u + H_{CURB}$.

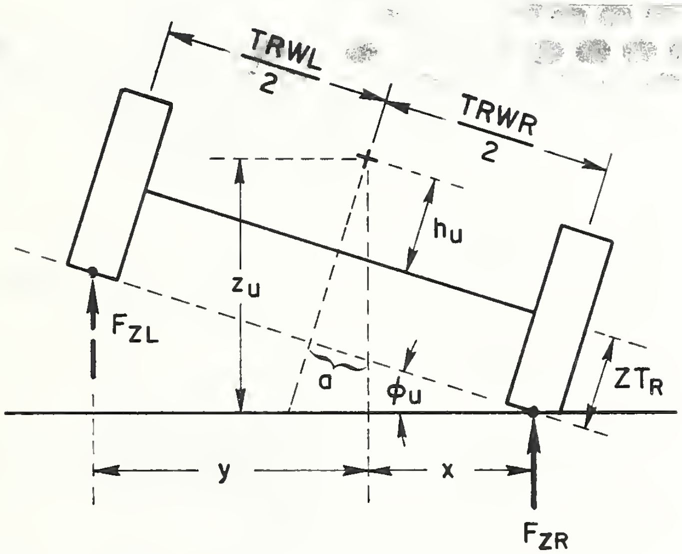
Therefore

$$I_u \ddot{\phi}_u = - F_{SL} \cdot s \cdot \cos \Delta\phi_s + F_{SR} \cdot s \cdot \cos \Delta\phi_s + F_{ZL} \cdot y - F_{ZR} \cdot x$$

$$- F_{YL} \cdot z_u - F_{YR} \cdot z_u + F_l \cdot h_{rc} \cdot \cos \Delta\phi_s$$

$$- F_d \cdot (z_u + H_{CURB})$$

When the vehicle begins to roll the moment arms for the vertical tire forces change as a function of the tire deflection and the unsprung mass roll angle. The car's track width (TRW) is divided into two parts, the left (TRWL/2) and the right (TRWR/2). This is due to the fact that they may be shortened due to structural deformation when contacting the curb. This all can be seen in the following:



$$x = (TRWR/2 - a) \cos \phi_u$$

$$a = (h_u + ZT_R) \tan \phi_u$$

Therefore

$$x = (TRWR/2) \cos \phi_u - (h_u + ZT_R) \sin \phi_u$$

$$y = TRW \cdot \cos \phi_u - x$$

Therefore

$$y = (TRWL/2) \cos \phi_u + (h_u + ZT_R) \sin \phi_u$$

Therefore

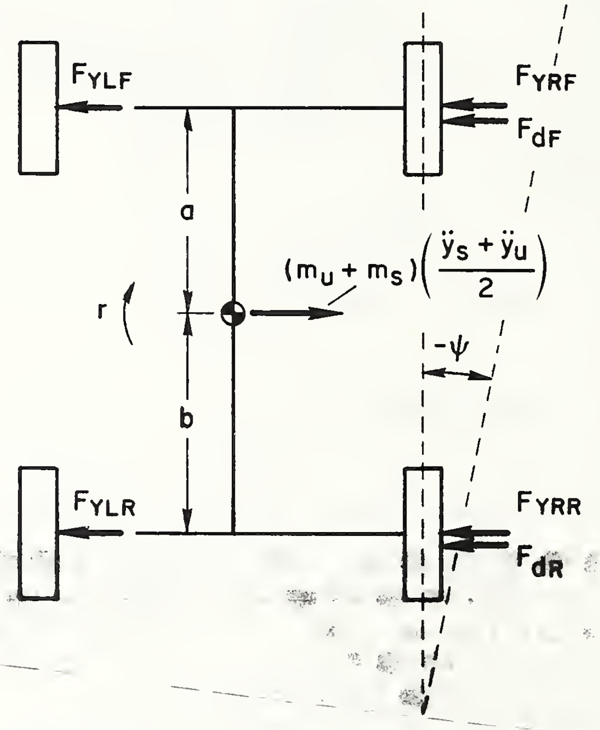
$$I_u \ddot{\phi}_u = (F_{SR} - F_{SL}) \cdot s \cdot \cos \Delta\phi_s + F_{ZL} \left[(TRWL/2) \cos \phi_u + (h_u + ZT_R) \sin \phi_u\right]$$

$$- F_{ZR} \left[(TRWR/2) \cos \phi_u - (h_u + ZT_R) \sin \phi_u\right] - F_{YL} \cdot z_u - F_{YR} \cdot z_u$$

$$+ F_l \cdot h_{rc} \cdot \cos \Delta\phi_s - F_d \cdot (z_u + H_{CURB})$$

Caution: The TRW/2 term may be shortened due to structural deformation due to contact with the curb. Therefore in this equation it is written for the particular side referenced (TRWR/2 or TRWL/2).

1.3 YAW AXIS (SPRUNG AND UNSPRUNG)

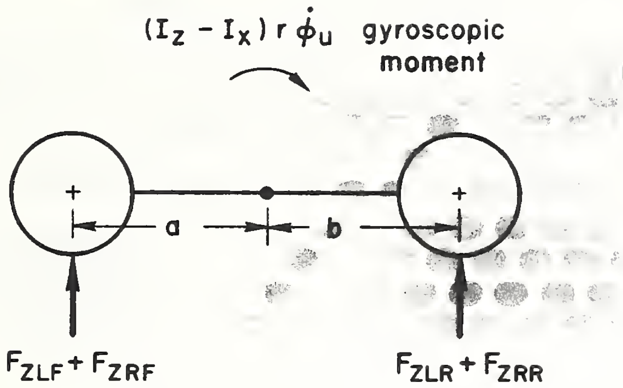


1.3.1 Moment Equation

$$I_z \dot{r} = -(F_{YLF} + F_{YRF} + F_{dF})\, a$$

$$+ (F_{YLR} + F_{YRR} + F_{dR})\, b + \dot{\phi}_s \dot{\theta}(I_x - I_y)$$

1.4 PITCH AXIS (SPRUNG AND UNSPRUNG)



1.4.1 Moment Equation

$$I_y \ddot{\theta} = (I_z - I_x) r \cdot \dot{\phi}_s - b(F_{ZLR} + F_{ZRR}) + a(F_{ZLF} + F_{ZRF})$$

1.5 TIRE/WHEEL FORCES

1.5.1 Tire Sliding Forces

For the sliding friction model. The side force is a function of: normal load, coefficient of friction, and side velocity, and can be expressed as

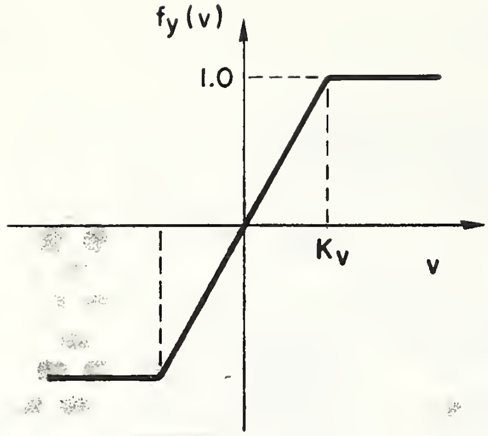
$$F_{YLF} = \mu \cdot F_{ZLF} \cdot f_y(\dot{y}_u + a \cdot r - \text{Roll Term})$$

$$F_{YRF} = \mu \cdot F_{ZRF} \cdot f_y(\dot{y}_u + a \cdot r - \text{Roll Term})$$

$$F_{YLR} = \mu \cdot F_{ZLR} \cdot f_y(\dot{y}_u - b \cdot r - \text{Roll Term})$$

$$F_{YRR} = \mu \cdot F_{ZRR} \cdot f_y(\dot{y}_u - b \cdot r - \text{Roll Term})$$

where $f_y(v)$ is determined from:



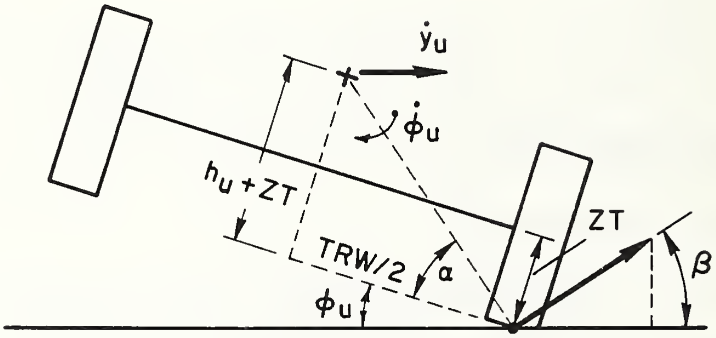
where,

$$v = \dot{y}_u + a \cdot r - \text{Roll Term}$$

or,

$$v = \dot{y}_u - b \cdot r - \text{Roll Term}$$

The roll term is the velocity caused by $\dot{\phi}_u$ as the vehicle is rolling. This is evaluated as follows:



$$\text{Roll Term} = \dot{\phi}_u \left[(h_u + ZT)^2 + \left(\frac{TRW}{2}\right)^2 \right]^{1/2} \cos \beta$$

where

$$\beta = 90 - \alpha - \phi_u$$

and

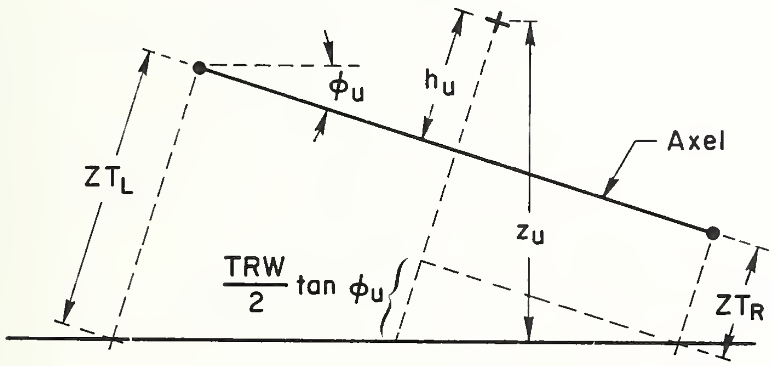
$$\alpha = \tan^{-1} \left[\frac{h_u + ZT}{TRW/2} \right]$$

1.5.2 Tire Normal Forces

The normal forces result from tire deflections determined by the distance between the axle and the road surface at each wheel. The distance depends on the c.g. height, z_u, and vehicle pitch and roll attitude (θ, ϕ_u). The forces include both spring constant and damping terms.

<u>Tire Deflections (Compression of Tire)</u>

For the right tires:



Therefore

$$ZT_R = \frac{-z_u}{\cos\phi_u} - h_u - \frac{TRW}{2}\tan\phi_u + \text{Pitch Term}$$

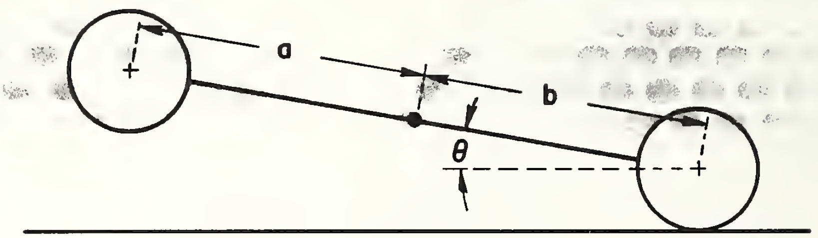
For the left tires:

$$ZT_L = ZT_R + TRW \cdot \tan\phi_u$$

Therefore

$$ZT_L = \frac{-z_u}{\cos\,\phi_u} - h_u + \frac{TRW}{2}\tan\,\phi_u + \text{Pitch Term}$$

For the pitch terms:



For the left and right front tires the pitch term is

$$a\,\tan\,\theta$$

For the left and right rear tires the pitch term is

$$-\,b\,\tan\,\theta$$

Therefore the axle heights above the ground are

$$ZT_{LF} = \frac{-z_u}{\cos\,\phi_u} - h_u + \frac{TRW}{2}\cdot\tan\,\phi_u + a\cdot\tan\,\theta$$

$$\dot{Z}T_{LF} = \frac{-\dot{z}_u}{\cos\,\phi_u} + \frac{\dot{\phi}_u\,(TRW/2 - z_u\cdot\sin\,\phi_u)}{\cos^2\,\phi_u} + \frac{a\cdot\dot{\theta}}{\cos^2\,\theta}$$

$$ZT_{RF} = \frac{-z_u}{\cos\,\phi_u} - h_u - \frac{TRW}{2}\cdot\tan\,\phi_u + a\cdot\tan\,\theta$$

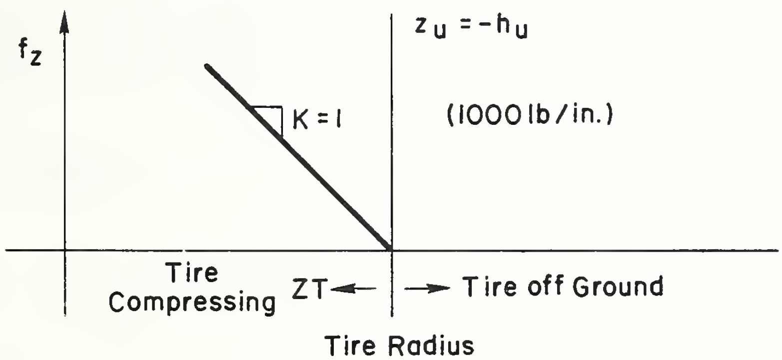
$$\dot{Z}T_{RF} = \frac{-\dot{z}_u}{\cos\,\phi_u} - \frac{\dot{\phi}_u\,(TRW/2 + z_u\cdot\sin\,\phi_u)}{\cos^2\,\phi_u} + \frac{a\cdot\dot{\theta}}{\cos^2\,\theta}$$

$$ZT_{LR} = \frac{-z_u}{\cos\ \phi_u} - h_u + \frac{TRW}{2} \cdot \tan\ \phi_u - b \cdot \tan\ \theta$$

$$\dot{Z}T_{LR} = \frac{-\dot{z}_u}{\cos\ \phi_u} + \frac{\dot{\phi}_u\ (TRW/2 - z_u \cdot \sin\ \phi_u)}{\cos^2\ \phi_u} - \frac{b \cdot \dot{\theta}}{\cos^2\ \theta}$$

$$ZT_{RR} = \frac{-z_u}{\cos\ \phi_u} - h_u - \frac{TRW}{2} \cdot \tan\ \phi_u - b \cdot \tan\ \theta$$

$$\dot{Z}T_{RR} = \frac{-\dot{z}_u}{\cos\ \phi_u} - \frac{\dot{\phi}_u\ (TRW/2 + z_u \cdot \sin\ \phi_u)}{\cos^2\ \phi_u} - \frac{b \cdot \dot{\theta}}{\cos^2\ \theta}$$



Using the axle heights and the plot from above, the force for each tire can be written as:

$$F_{ZT} = K_z f_z(ZT) + B_z \cdot \dot{Z}T$$

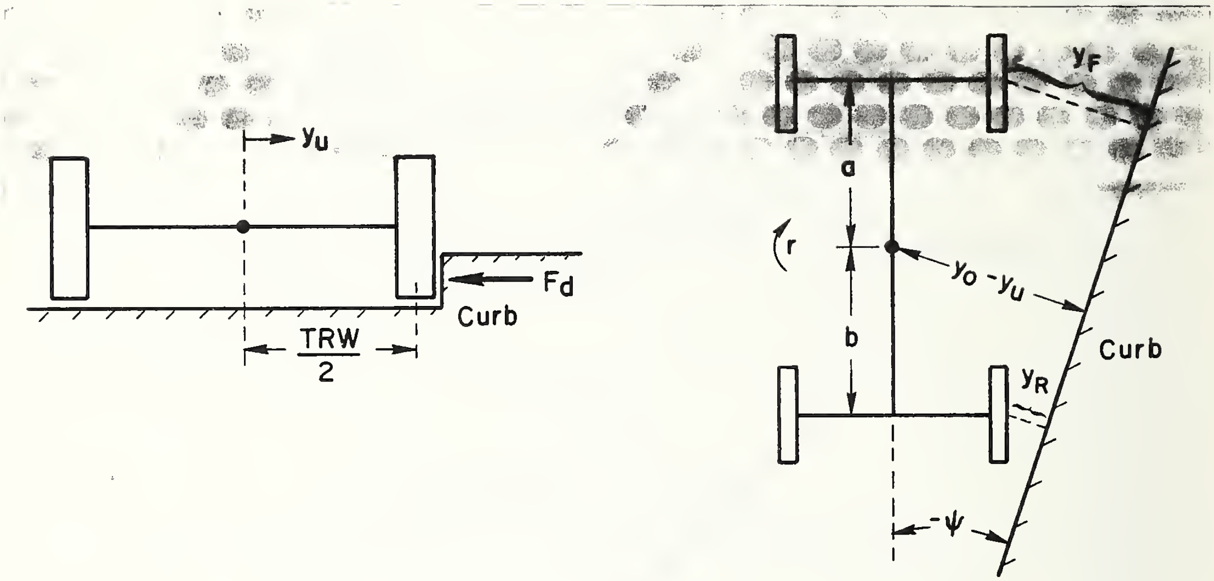
where

$$K_z \text{ and } B_z = 0 \quad \text{for} \quad |ZT| > \text{Tire Radius}$$

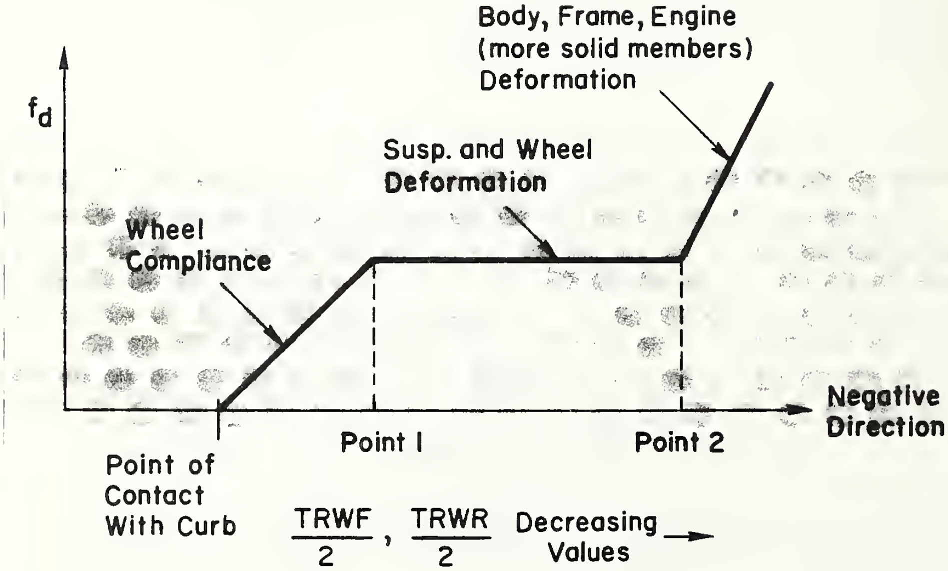
$$F_{ZT} = K_z\ [(\text{Tire Radius}) - ZT_i] - B_z \cdot \dot{Z}T_i$$

1.5.3 Road Surface Lateral Force vs. Displacement Characteristic at the Discontinuity

Road surface discontinuity is assumed to cause both elastic and plastic deformation in wheel/suspension structure.



y_o = initial conditions for starting distance of m_u c.g. from curb



$$y_F = y_o - y_u - a \cdot \sin\psi - (TRWF/2)\cos\psi$$

$$\dot{y}_F = -\dot{y}_u - a \cdot r \cdot \cos\psi + (TRWF/2)\, r \cdot \cos\psi$$

$$y_R = y_o - y_u + b \cdot \sin\psi - (TRWR/2)\cos\psi$$

$$\dot{y}_R = -\dot{y}_u + b \cdot r \cdot \cos\psi + (TRWR/2)\, r \cdot \sin\psi$$

$$F_{dF} = f_d(y_F) - B_d\dot{y}_F$$

$$F_{dR} = f_d(y_R) - B_d\dot{y}_R$$

$$\frac{TRWF}{2} = \frac{(y_o - y_u - a \cdot \sin\psi)}{\cos\psi} \text{ for } y_F < \frac{TRW}{2}, \text{ otherwise } \frac{TRWF}{2} = \frac{TRW}{2}$$

$$\frac{TRWR}{2} = \frac{(y_o - y_u + b \cdot \sin\psi)}{\cos\psi} \text{ for } y_R < \frac{TRW}{2}, \text{ otherwise } \frac{TRWR}{2} = \frac{TRW}{2}$$

2.0 NUMERICAL SOLUTION

2.1 VERTICAL TIRE FORCES

Given z_u, ϕ_u, θ ; $\dot{z}_u$, $\dot{\phi}_u$, $\dot{\theta}$

Compute axle heights ZT_i, $\dot{Z}T_i$ (1.5.2)

Given tire force vs. deflection f_z (ZT)

Compute tire normal loads F_{zi}

2.2 LATERAL TIRE SLIDING FORCES

Given F_{zi}, $\dot{y}_u$, r ; Compute F_{yi} (1.5.1)

2.3 LATERAL FORCE AT DISCONTINUITY

Given y_u, ψ, r ; Compute y_F, $\dot{y}_F$, y_R, $\dot{y}_R$ (1.5.3)

Given y_F, $\dot{y}_F$, y_R, $\dot{y}_R$ and discontinuity force vs. deflection f_d (y.);

Compute F_{dF}, F_{dR}, TRWF/2, TRWF/2 (1.5.3)

2.4 ROLL CENTER FORCES AND SPRUNG MASS ROLL ACCELERATION

Given ϕ_u, ϕ_s, y_u, y_s, $\dot{\phi}_u$, $\dot{\phi}_s$, $\dot{y}_u$, $\dot{y}_s$, z_s, z_u, $\dot{z}_s$, $\dot{z}_u$;

Compute Spring Deflections and Rates (1.1.4)

Given Spring Deflections and Rates, f_s

Compute suspension forces F_{SL}, F_{SR} (1.1.4)

Given ϕ_s, ϕ_u, y_s, y_u, z_s, z_u, $\dot{\phi}_s$, $\dot{\phi}_u$, $\dot{y}_s$, $\dot{y}_u$, $\dot{z}_s$, $\dot{z}_u$, F_{SL}, F_{SR};

Compute $\ddot{\phi}_s$, F_1, (1.1.1, 1.1.2, 1.1.3)

2.5 COMPUTE UNSPRUNG MASS MOTIONS

Given F_1, F_{SL}, F_{SR}, ϕ_s, ϕ_u, tire side forces, tire normal forces;

Compute $\ddot{y}_u$, $\ddot{z}_u$, $\ddot{\phi}_u$ (1.2.1, 1.2.2, 1.2.3)

Given tire forces, r, $\dot{\phi}_u$;

Compute $\dot{r}$, $\ddot{\theta}$ (1.3, 1.4)

2.6 UPDATE VELOCITIES, ORIENTATION, AND POSITION

Given $\ddot{\theta}$, $\ddot{\phi}_s$, $\ddot{\phi}_u$, $\dot{r}$, $\ddot{y}_u$, $\ddot{z}_u$

Integrate to obtain updated states and rates

APPENDIX B

CREATING THE VEHICLE CHARACTERISTIC INPUT FILE

A. OVERVIEW

The tripped roll over simulation program is designed so that various vehicles may be tested. To allow the user easy installation of each vehicle to be tested, a program was designed to create an input file that contains the necessary physical characteristics of each vehicle. The following discussion will explain how '. use the program and will define each of the characteristics that the user must enter.

To run the program from DOS the user types either TRFILECR for the unsprung model or SPFILECR for the sprung mass model (underlined phrases define user inputs) while defaulted to the correct disk drive. The program will initially ask for a file name. The name should include the disk drive specifier (if necessary) a file extension if desired and a prefix to define which model it is set up for (e.g., A:STRNOVA.75). Once the file name has been input the pro; am will prompt the user to enter the vehicle's characteristics. Examples for the two programs are given at the end of this appendix. Car parameters are defined in Table B-1, and values for a 1975 Chevrolet Nova are given in Table B-2.

Before any parameter file is created, the user should thoroughly read Appendix D -- Parameter Definitions and Specification. Appendix D gives a descripiton of each parameter, including the units, and where they can be found in the equations of motion. Furthermore, Appendix D gives a detailed explanation on how to find some of the uncommon parameters required by the programs.

B. TRFILECR (Unsprung Mass Program Parameters)

```
ENTER FILE NAME (TYPE Q TO QUIT)

? TRNOVA.75

ENTER THE CAR PARAMETERS IN THE FOLLOWING ORDER:

     ALPHA,BETA,TRW,HU,KZ,BZ,CF
     BD,KD1,KD2,MU,IX,POINT1,POINT2
     IY,IZ,IY,WHLDEF,KV,TRAD,HCURB

SEE PROGRAM LISTING OR USER'S GUIDE FOR REFERENCES TO THE ABOVE
TERMINOLOGY

? 4.45,4.8,5,1.64,12000,80,.75
? .25,24000,96000,121.7,330,.16667,.6667
? 2240,2240,132,4000,1,1,.5
```

C. SPFILECR (sprung mass model parameters)

```
ENTER FILE NAME (TYPE Q TO QUIT)

? STRNOVA.75

ENTER THE CAR PARAMETERS IN THE FOLLOWING ORDER:

     ALPHA, BETA, TRW, HU, KZ, BZ, CF, BD
     KD1, KD2, MU, HR, SUSK1, SUSK2, B1, B2
     IX, IY, IZ, HS, IU, WHLDEF, KV, POINT1, POINT2
     MS, IS, TRAD, HCURB, S, SPRNGK, SPRLNG, ABSDEF, BL

SEE PROGRAM LISTING OR USER'S GUIDE FOR REFERENCES TO
THE ABOVE TERMINOLOGY

? 4.45,4.8,5,.2,12000,80,.75,.25
? 24000,96000,16.7,1,6900,33000,325,33
? 330,2240,2240,1.2,132,4000,1,.1667,.6667
? 105,240,1,.5,1.75,200000,.6667,.25,1000
```

TABLE B-1. CHASSIS PARAMETERS, CHEVY NOVA 1975 MODEL

m_s	=	sprung mass	105 lb-sec^2/ft
h_s	=	m_s c.g. to sprung mass bottom	1.20 ft
g	=	gravity	32.2 ft/sec^2
I_s	=	sprung mass roll inertia	240 lb-ft-sec^2
s	=	sprung base/2	1.75 ft
K_1	=	suspension spring constant	6900 lb/ft
B_1	=	suspension spring damping constant	325 lb-sec/ft
B_2	=	bump stop damping constant	33 lb-sec/ft
K_2	=	bump stop spring constant	33,000 lb/ft
m_u	=	unsprung mass	16.7 lb-sec^2/ft
TRW	=	track width	5 ft, or TRW/2 = 2.5 ft
I_x	=	total inertia in roll	330 lb-ft-sec^2
a	=	m c.g. to front axle	4.45 ft
b	=	m c.g. to rear axle	4.80 ft
I_z	=	total inertia in yaw	2240 lb-ft-sec^2
I_u	=	total front and rear unsprung mass inertia in roll	132 lb-ft-sec^2
μ	=	coefficient of friction	0.75
K_z	=	single tire rate	12,000 lb/ft
B_z	=	single tire damping	80 lb-sec/ft

APPENDIX C

DISK CONTENTS

The directory (<u>DIR</u>) of the tripped roll over disk contains the following:

COMMAND	COM	17664	3-08-83	12:00p
SPTRIP87	EXE	50464	6-04-85	10:36a
TRIP87	EXE	46336	6-04-85	2:02p
SPTRIP	BAS	35881	6-04-85	9:04a
TRIP	BAS	`28988	6-04-85	1:36p
SPFILECR	EXE	20040	5-30-85	8:57a
TRFILECR	EXE	19624	5-30-85	8:49a
SPFILECR	BAS	1114	5-30-85	8:53a
TRFILECR	BAS	893	5-30-85	8:39a
GRAPHICS	COM	789	3-08-85	12:00p
SPNOVA	75	256	3-26-85	12:04p
TRNOVA	75	128	3-26-85	11:56a
AUTOEXEC	BAT	78	4-03-85	7:56a
	14 File(s)		106496 bytes free	

Each of the files above will now be discussed so that the user will be familiar with all the files on the disk.

COMMAND.COM - This allows the computer to startup and load the files for execution.

SPTRIP87.EXE - This is the compiled version of the program that is described in this paper.

TRIP87.EXE - This is the compiled version of less complex version of SPTRIP.EXE.

SPTRIP.BAS - This is the basic interpreter version (code) of the program described in this paper.

TRIP.BAS - This is an earlier version of SPTRIP.BAS without the sprung mass degree-of-freedom. If the springs in SPTRIP.BAS are stiffened so that the sprung and unsprung masses are essentially rigid, the results from SPTRIP.BAS and TRIP.BAS should be similar. The reader is referred to Section II-C, Cases 21-26, and Figs. 11-13. Because TRIP.BAS is less complex it will run faster and save time.

SPFILECR.EXE	-	This is the compiled version of SPFILECR.BAS which will be discussed below.
TRFILECR.EXE	-	This is the compiled version of TRFILECR.BAS which will be discussed below.
SPFILECR.BAS	-	This program is used with the SPTRIP program. It enables the user to create a file of constant car parameters that are needed in the SPTRIP program. For a more detailed look at this program the reader is referred to Appendix B.
TRFILECR.BAS	-	This program is used with the TRIP program. It enables the user to create a file of constant car parameters that are needed in the TRIP program. This program is very similar to SPFILECR.BAS except that less inputs are needed because the sprung mass is no longer present. TRFILECR.BAS can be used by following Appendix B and omitting the parameters HR, SUSK1, SUSK2, B1, B2, HS, MS, IS, S, SPRUNGK, SPLNG, ABSDEF, and BL.
GRAPHICS.COM	-	This program allows the user to printout the time histories that the SPTRIP and TRIP programs create. This must be installed before SPTRIP and TRIP are run.
SPNOVA.75	-	This is a file of the constant car parameters that were used in testing SPTRIP. The car used was a 1975 Chevy Nova.
TRNOVA.75	-	This is a file of the constant car parameters that were used in testing TRIP.
AUTOEXEC.BAT	-	This file installs the graphics made, date, time, and heading when the computer is booted, or switched on.

APPENDIX D

PARAMETER DEFINITIONS AND SPECIFICATIONS

A. INTRODUCTION AND OVERVIEW

Based on experience gained by using the "Tripped Rollover" programs, this appendix has been written to help the user define all of the necessary parameters. Table D-1 lists each parameter, their units, and on what page in the Equations of Motion Appendix (Appendix A) the parameter is found. In addition to Table D-1, several points are included below that will provide useful guidance to the user, regarding parameter variations.

B. MODIFIED PARAMETER DEFINITIONS (TABLE D-1, FIGURE D-1)

1. Sprung Mass Height

HS (h_s) plus SPRLNG add up to the sprung mass center of gravity height above the axle centerline. The value for SPRLNG is not obtainable from static tests or published literature, and is in fact a redundant parameter. HS can be set to equal the entire distance from the c.g. to the axle, and SPRLNG is then set equal to zero, c.g. height is obtainable from static test data or published literature. A simple approximation is that c.g. height = 0.39 × roof height, as supported by data in Fig. D-2. Referring to Fig. D-1, finally note that

$$h_s = h_{c.g.} - T_R$$

2. Equivalent Spring Rates

SUSK1 (K_1), SUSK2 (K_2), B1 (B1), B2 (B2) should be set to their equivalent value acting at the wheels, and S (S) should be set = $\frac{TRW}{2}$. The reason for this suggested approach is that the main effect of the springs on tip-over is their effect on roll stiffness. The roll stiffness is normally obtained from static tests which provide a stiffness parameter K_{ROLL} in ft/lbs of moment/radian of roll angle.

In a simple case of a suspension spring = K_1, this roll stiffness would be equal to $2K_1S^2$. But with the addition of auxiliary roll stiffness devices (anti-roll bars), the roll stiffness is higher than $2K_1S^2$. When setting spring rates to act at the wheel, S = $\frac{TRW}{2}$, then

$$2K_1S^2 = \frac{K_1\ (TRW)^2}{2} = K_{ROLL}$$

or

$$K_1 = \frac{(2)\ K_{ROLL}}{(TRW)^2}$$

3. Default Values

Several parameters in the model are primarily included to minimize numerical instability problems and should not affect rollover potential. The parameters are not related to actual physical measurements, and default values should be provided as follows:

KV = 1

SPRNGK = 200,000

BL = 1000

C. INITIAL CONDITIONS

In order to provide stable initial conditions when the vehicle is placed in a sliding motion, the steady-state roll angle and tire deflections for the side-slide conditions should be entered as program inputs. If this is not done, the vehicle is subjected to a step input lateral sliding friction force. This causes the vehicle to bounce and roll which in some cases can cause the vehicle to rollover before striking the curb. This transient may also lead to inaccurate estimates for the minimum lateral sliding speed needed for tripped rollover.

The equations given in Table D-2 should be used to calculate initial conditions for ϕ_u, ϕ_s, Z_u. An example calculation is given in Table D-3. Figures D-3 - D-6 show example computer runs with and without the corrected values. These examples were run in the initial velocity iteative mode, and the plots shown are for the final critical side velocity iteration.

D. NON-TRIPPED TIP-OVER CONDITIONS

A vehicle can tip-over due to moments generated under sideways sliding conditions. The conditions under which this can happen are described by the equation

$$F_{Z1} = \frac{Mg}{2} - \frac{M_s\, g\mu}{(TRW)} [h_s + T_R] - \frac{M_u\, g\mu}{(TRW)} [T_R + h_u]$$

where F_{Z1}, is the total force on the two unloading tires.

Whenever F_{Z1} is ≤ 0, the vehicle will tip-over during sliding. If the program is run under these conditions in the velocity iteration mode, the program will find the critical side-slide velocity to be zero. By setting the above equation to zero, the c.g. height that will lead to slide induced rollover can be calculated. Note that for the 5 degrees-of-freedom model (i.e., no sprung mass) the second right hand side term in the above equation must be dropped.

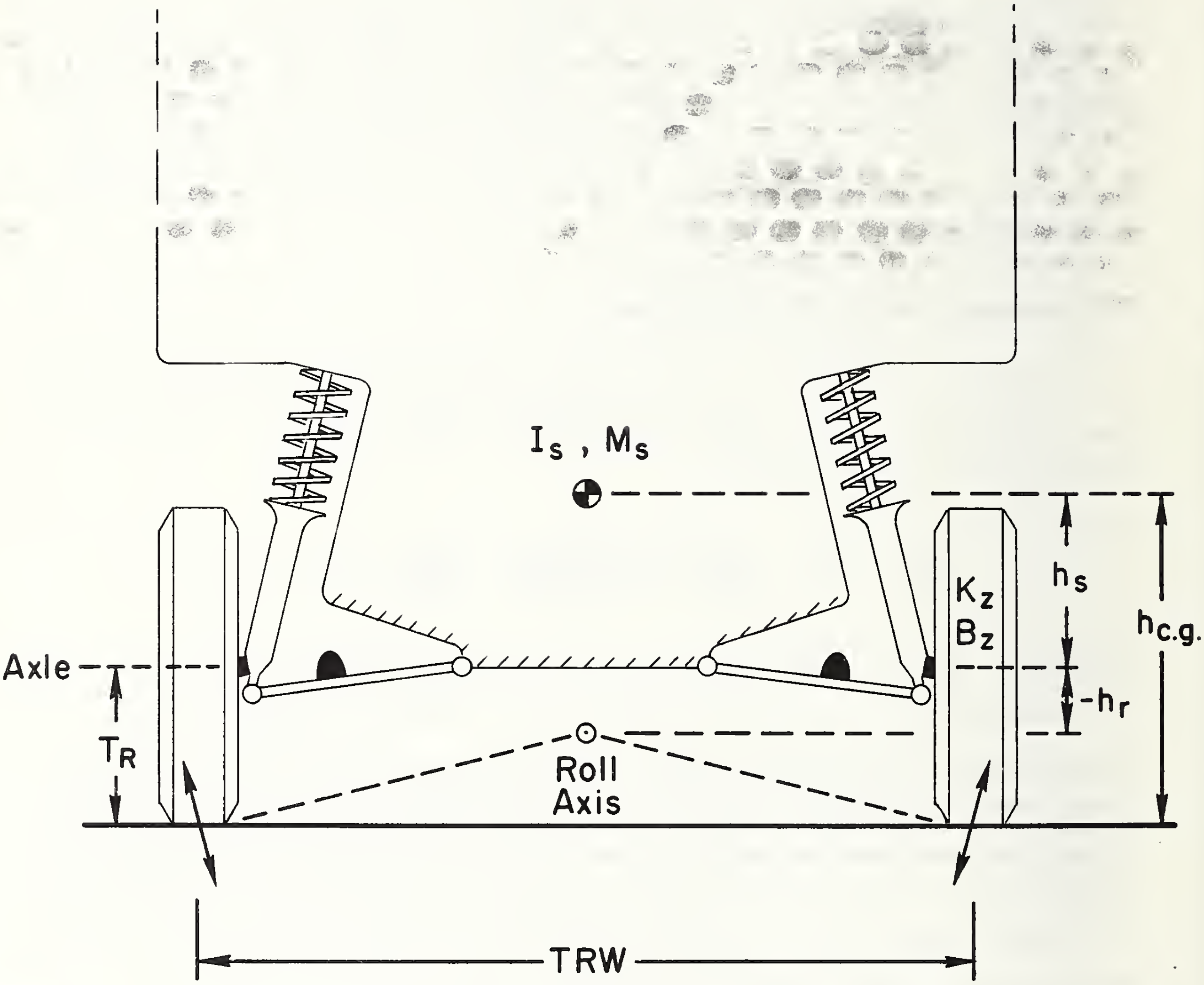


Figure D-1. Revised Parameter Definitions

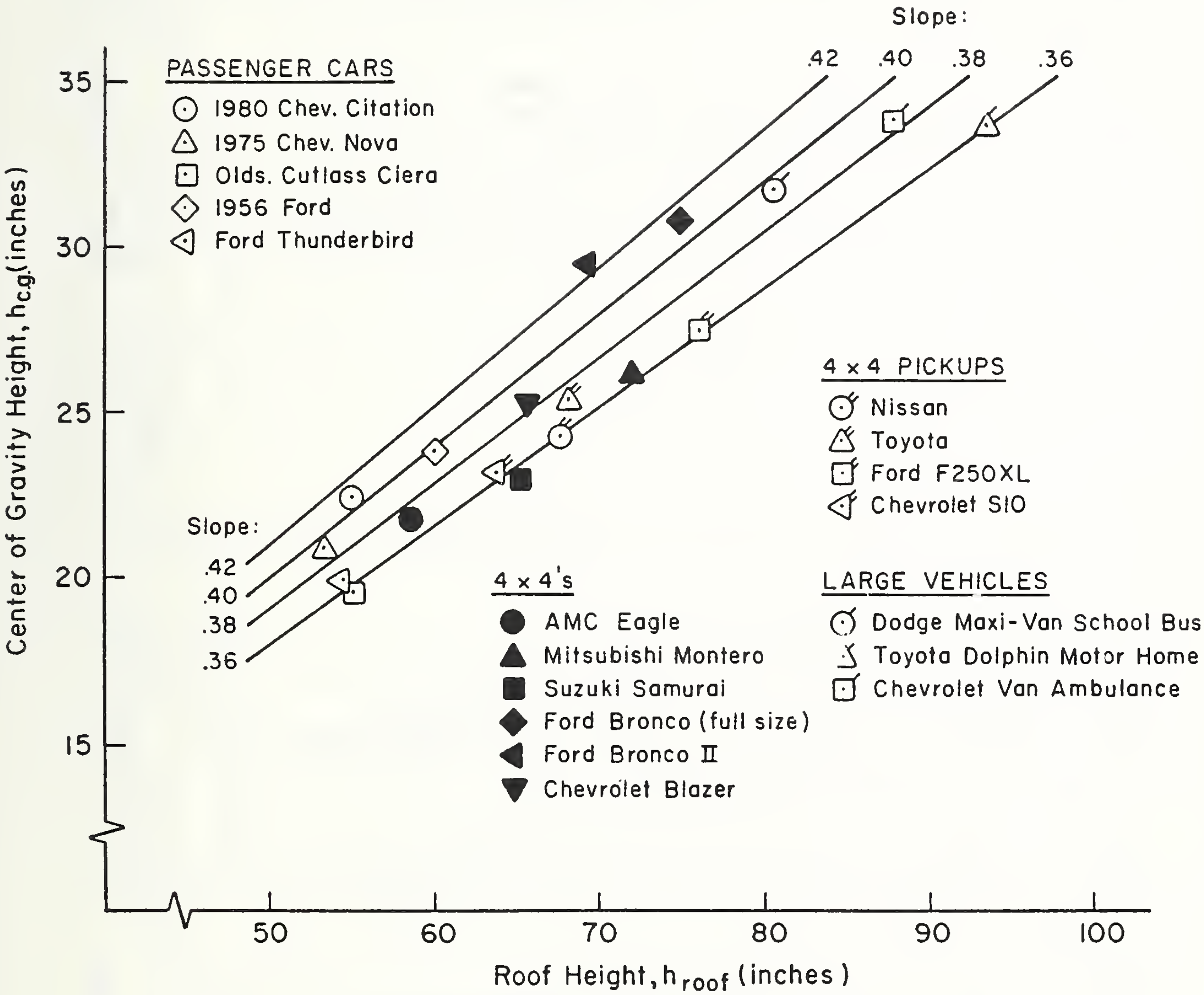


Figure D-2. Relationship Between Vehicle Center of Gravity Height and Roof Height

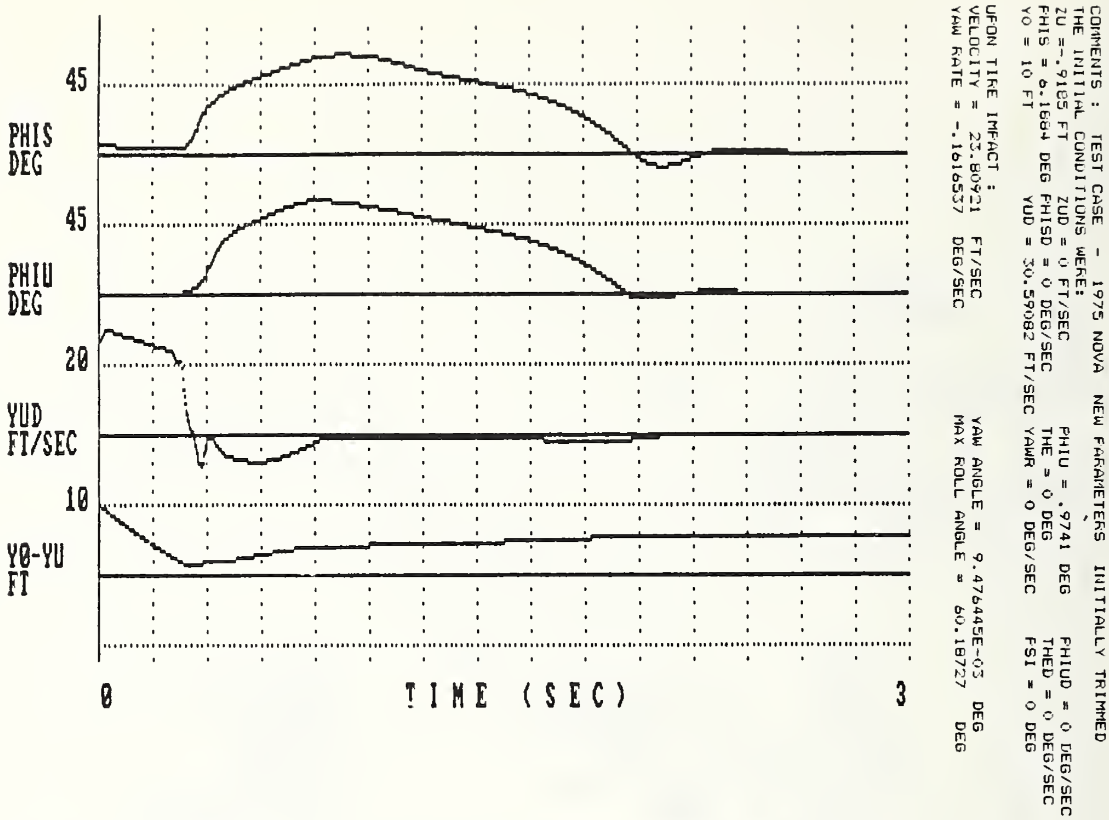


Figure D-3. 1975 Nova Test Case at Critical Side Velocity: Trimmed

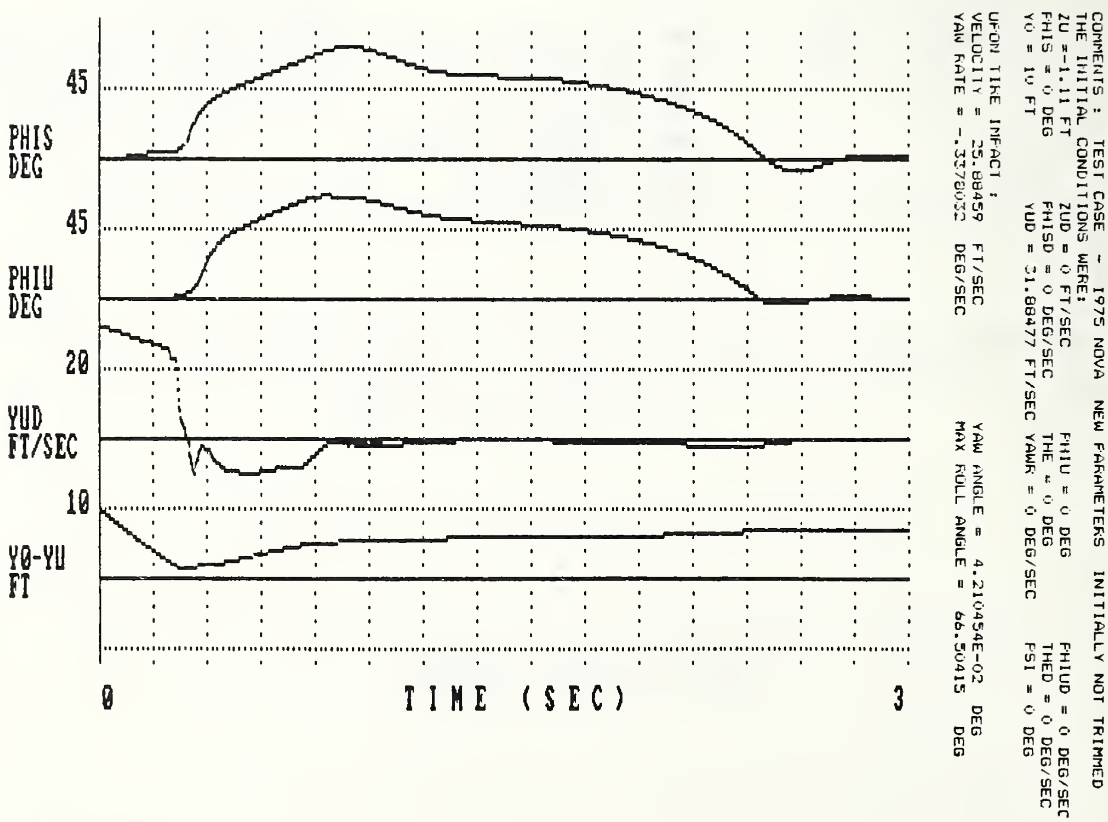


Figure D-4. 1975 Test Case at Critical Side Velocity: Not Trimmed

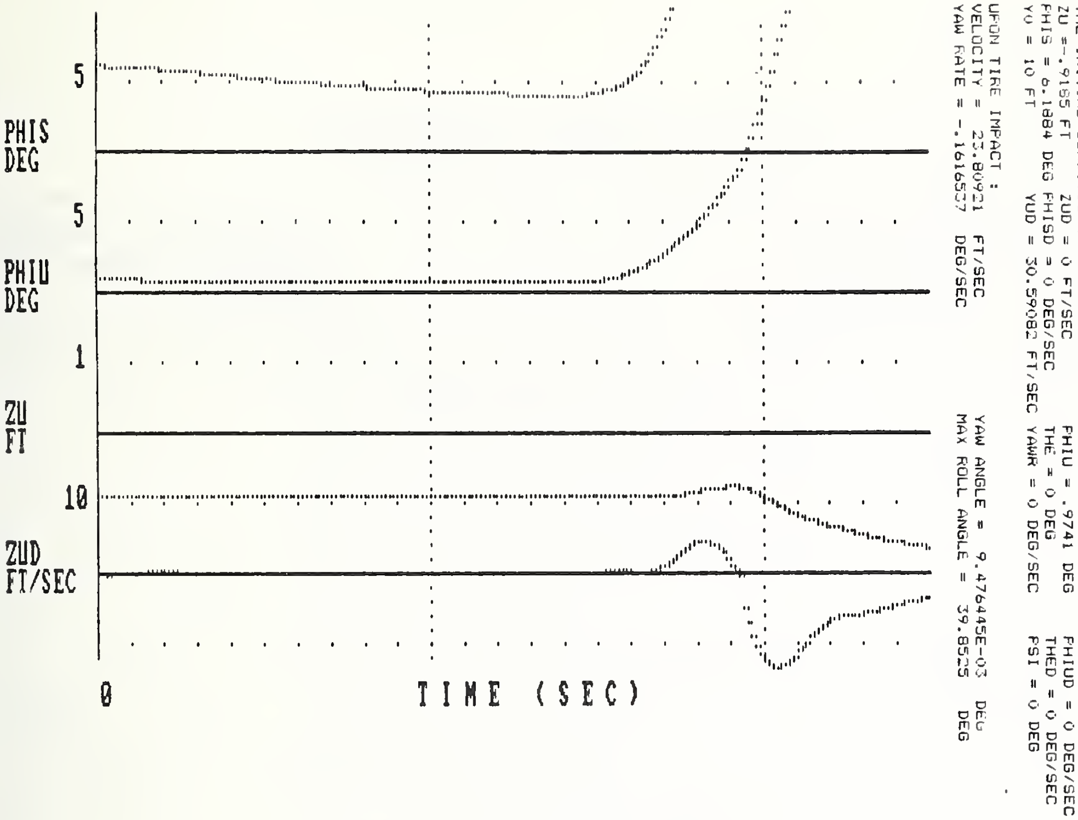


Figure D-5. 1975 Nova Test Case Initial Transients: Trimmed

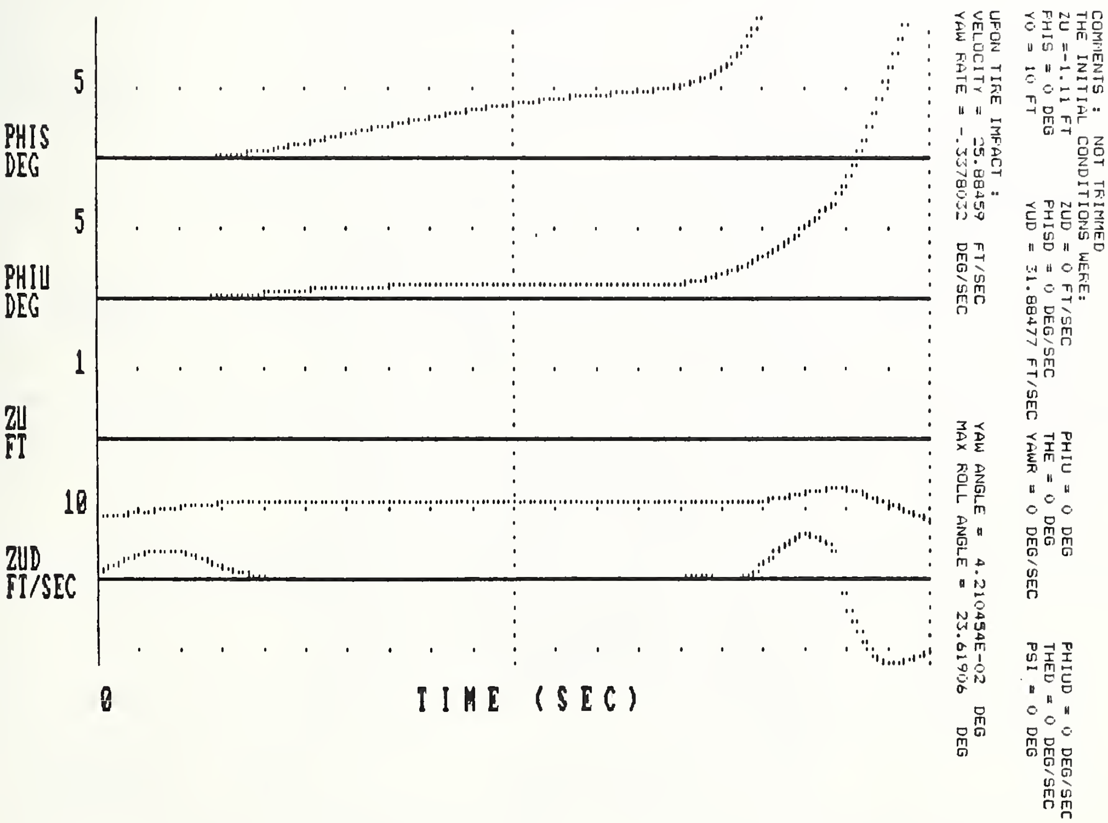


Figure D-6. 1975 Nova Test Case Initial Transients: Not Trimmed

TABLE D-1. PARAMETER DEFINITIONS
FOR TRIPPED ROLLOVER MODEL

PROGRAM VARIABLE	APPENDIX A VARIABLE		SEE ON PAGE NO.	UNITS
ALPHA	a	Horizontal distance from the vehicle center of gravity to front axle	A-1	ft
BETA	b	Horizontal distance from the vehicle center of gravity to the rear axle	A-1	ft
TRW	TRW	Total track width (average of front and rear)	A-1	ft
HU	h_u	Height of unsprung mass center of gravity above axle centerline (usually zero)	A-8	ft
KZ	K_z	Single tire radial spring rate	A-17	lbs/ft
BZ	B_z	Single tire radial damping rate	A-17	$\frac{\text{lbs-sec}}{\text{ft}}$
CF	μ	Coefficient of friction between the tire ground	A-13	--
BD	B_d	Vehicle structure damping constant in the lateral deformation direction	A-19	$\frac{\text{lbs-sec}}{\text{ft}}$
KD1	--	Wheel and suspension lateral deflection spring rate when striking the curb	A-18	lbs/ft
KD2	--	Slope of force vs. lateral deformation of body, frame, and engine when striking the curb	A-18	lbs/ft
MU	M_u	Total unsprung mass	A-10	$\frac{\text{lbs-sec}^2}{\text{ft}}$

TABLE D-1. (Continued)

PROGRAM VARIABLE	APPENDIX A VARIABLE		SEE ON PAGE NO.	UNITS
HR	h_r	Height of the lateral restraining force member (roll axis) above the axle center-line (average front and rear)	A-8	ft
SUSK1	K_1	Suspension spring rate per side equivalent acting at wheel	A-4	lbs/ft
SUSK2	K_2	Bump stop spring rate per side, equivalent acting at wheel	A-4	lbs/ft
B1	B_1	Suspension shock absorber damping rate per side, equivalent acting at wheel	A-4	$\frac{\text{lbs-sec}}{\text{ft}}$
B2	B_2	Bump stop damping rate per side, equivalent acting at wheel	A-4	$\frac{\text{lbs-sec}}{\text{ft}}$
IX	I_x	Total roll inertia about total mass center of gravity	A-12	lb ft/sec^2
IY	I_y	Total pitch inertia	A-12	lb ft/sec^2
IZ	I_z	Total yaw inertia	A-12	lb ft/sec^2
HS	h_s	Height of sprung mass center of gravity above axle centerline	D-2	ft
IU	I_u	Total unsprung mass roll inertia about M_u center of gravity	A-10	lb ft/sec^2

TABLE D-1. (Continued)

PROGRAM VARIABLE	APPENDIX A VARIABLE		SEE ON PAGE NO.	UNITS
WHLDEF	--	Constant force during crush deformation of the "soft" suspension and wheel members when striking a curb	A-18	lbs
KV	K_V	Velocity at which tire slides with a constant side velocity function	A-14	ft/sec
POINT1		Deflection distance at which wheel and suspension begin to crush (permanent deformation)	A-18	ft
POINT2		Crush distance at which the more solid members of the body, frame, and engine become involved in lateral deformation	A-18	ft
MS	M_s	Total sprung mass	D-2	$\frac{lb\ sec^2}{ft}$
IS	I_s	Sprung mass roll inertia about its center of gravity	D-2	lb ft/sec^2
TRAD	T_R	Tire radius	D-2	ft
HCURB	H_{CURB}	Curb height	A-10	ft
S	s	With the suspension spring rates set to equivalent acting at the wheels, the value for s should be set = TRW/2		ft
SPRNGK	K	Bushing (lateral restraining force) spring constant	A-8	lbs/ft

TABLE D-1. (Concluded)

PROGRAM VARIABLE	APPENDIX A VARIABLE		SEE ON PAGE NO.	UNITS
SPRLNG	--	Redundant term, always set = zero	--	--
ABSDEF	--	Vertical wheel travel distance from the static position of the wheel to the point where contact with the suspension bump stop begins	--	ft
BL	B	Bushing (lateral restraining force) damping constant	A-8	$\frac{\text{lb-sec}}{\text{ft}}$

TABLE D-2. INITIAL CONDITIONS TO ACHIEVE STEADY-STATE SLIDING CONDITIONS IN THE TRIPPED ROLLOVER PROGRAM

$$\phi_u = \frac{M_u g \mu \lfloor T_R + h_u \rfloor + M_s g \mu \lfloor h_s + T_R \rfloor}{K_z \,(TRW)^2}$$

$$\phi_s = \frac{M_s g \mu \lfloor h_s - h_r \rfloor}{K_{ROLL}} + \phi_u$$

where K_{ROLL} is total vehicle roll stiffness

Initial condition for static tire deflection

$$Z_u = T_R + h_u - \frac{(M_u + M_s)g}{4\, K_z}$$

TABLE D-3. EXAMPLE INITIAL CONDITION CALCULATIONS

$M_u = 16.7$	$TRW = 5$
$g = 32.2$	$\boxed{h_r = -0.5}$
$\mu = 0.75$	$\boxed{K_1 = 3000}$
$T_R = 1.0$	$\boxed{S = 2.5}$
$M_s = 105$	$\boxed{h_u = 0}$
$\boxed{h_s = 0.85}$	$\boxed{SPRLNG = 0}$
$K_z = 12{,}000$	

$$K_{ROLL} = 2K_1\ S^2 = 2\ (3000)\ (6.25)$$

$$\phi_u = \frac{(16.7)\ (32.2)\ (0.75)\ (1.0) + 105\ (32.2)\ (0.75)\ (1.85)}{12{,}000\ (25)}$$

$$= 0.017 \text{ radians } (0.97°)$$

$$\phi_s = \frac{105\ (32.2)\ (0.75)\ (1.35)}{37{,}500} + \phi_u = 0.108 \text{ radians } (6.2°)$$

$$Z_u = 1.0 - \frac{(121.7)\ 32.2}{48{,}000} = 0.9185 \text{ feet}$$

$\boxed{}$ Parameters changed from Reference test case.